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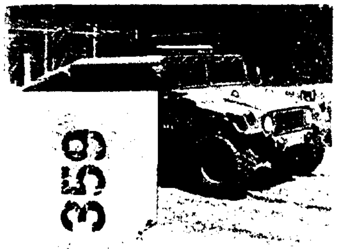

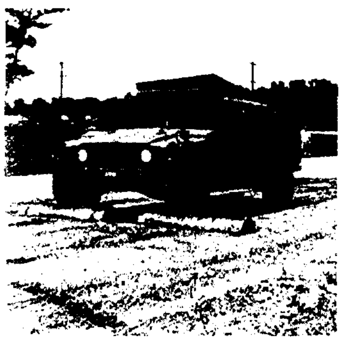

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TECHNICAL REPORT GL-86-18

COMPARISON OF MEASURES OF VIBRATION AFFECTING OCCUPANTS OF MILITARY VEHICLES

by

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The work reported herein was undertaken as an initial step in clarifying a clouded issue between two vibration measures for describing vehicle ride performance. It focused on the vertical component of human vibration in a vehicle ride dynamics setting and made experimental measurements of both vibration measures. Using test facilities in the Federal Republic of Germany and the United States, numerous vehicles in common use by NATO forces were studied under proving-ground conditions to assemble a data base of recorded driver-seat accelerations. These were analyzed to infer their corresponding Absorbed Power and International Organization for Standardization (ISO) acceleration measures.

The two vibration measures were found to be essentially the same in terms of their ability to express vehicle ride performance and differences in subjective vibratory

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roughness. The confounding effects of psychological factors, potential for injury, and time of exposure were identified as common problems needing further investigation. These factors are discussed in terms of accumulated experience with both measures.

Recommendations are made for a more thorough testing involving all components of vibration. Future tests should include medically trained individuals accustomed to dealing with human test subjects. It is also recommended that both measures continue to be used while experience accumulates with ISO acceleration with the eventual aim of incorporating the best features of both measures into a refined ISO measure to be used exclusively.

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EXECUTIVE SUMMARY

During the last two decades, two measures of the intensity of human vibration have been evolving along essentially independent lines. One is Absorbed Power, developed by the US Army Tank-Automotive Command (TACOM) in 1966. The other is a weighted root-mean-square acceleration developed by the International Organization for Standardization (ISO) in 1974.

Usage of these two measures by parties interested in vehicle ride dynamics is by no means uniform. As an example, in the United States, the Army Mobility Model (AMM) uses Absorbed Power to determine vehicle ride performance while NATO allies, who use the AMM-derived Nato Reference Mobility Model (NRMM) prefer ISO acceleration. Confusion and friction have accompanied these practices.

The work reported herein was undertaken as an initial step in clarifying a clouded issue. It focused on the vertical component of human vibration in a vehicle ride dynamics setting and made experimental measurements of both vibration measures. Using test facilities in the Federal Republic of Germany and the United States, numerous vehicles in common use by NATO forces were studied under proving-ground conditions to assemble a data base of recorded driver-seat accelerations. These were analyzed to infer their corresponding Absorbed Power and ISO acceleration measures.

The two measures were essentially the same in terms of their ability to express vehicle ride performance and differences in subjective vibratory roughness. The confounding effects of psychological factors, potential for injury, and time of exposure were identified as common problems needing further investigation. These factors are discussed in terms of accumulated experience with both measures.

Recommendations are made for a more thorough testing involving all components of vibration. Future tests should include medically trained individuals accustomed to dealing with human test subjects. It is also recommended that both measures continue to be used while experience accumulates with ISO acceleration with the eventual aim of incorporating the best features of both measures into a refined ISO measure to be used exclusively.

PREFACE

The study reported herein was sponsored by Department of the Army under the In-House Laboratory Independent Research program and was conducted under Project No. 4A161101A91D for the Assistant Secretary of the Army (R&D).

The study was conducted during the period 1984 through 1986 by Messrs. N. R. Murphy, Jr., Mobility Systems Division (MSD), Geotechnical Laboratory (GL), and F. H. Ahmad, Design and Development Branch (DDB), Instrumentation Services Division (ISD), US Army Engineer Waterways Experiment Station (WES). General supervision was provided by Dr. W. F. Marcuson, Chief, GL, Messrs. C. J. Nuttall, Chief, MSD; G. P. Bonner, Chief, ISD, and B. E. Reed, Chief, DDB, ISO.

Special acknowledgement is made to Dr. Dieter Wiegand, Erprobungsstelle 41 Der Bundeswehr-Trier, West Germany, for his assistance and personal involvement in the tests at Trier; Messrs. B. E. Reed, ISD, for his assistance in the field tests and data processing; Trevor Norsworthy and Kenworth Truck Company for the Endevco ride meter to process data in accordance to the International Organization of Standardization specifications; and members of the Future Armored Vehicles Research Coordinating Committee for arranging the joint United States-Germany testing at Trier.

COL Allen F. Grum, USA, was the previous Director of WES. COL Dwayne G. Lee, CE, is the present Commander and Director. Dr. Robert W. Whalin is Technical Director.

CONTENTS

COMPARISON OF MEASURES OF VIBRATION AFFECTING OCCUPANTS OF MILITARY VEHICLES

PART I: INTRODUCTION

Background

1. Today two predominant methods are used by the military to describe the effects of vehicle vibrations and human response: the Absorbed Power method (used largely in the United States) and the International Organization for Standardization (ISO) method (used extensively throughout European countries as well as in the United States). The two methods are similar in that both use frequency-weighted accelerations corresponding to greatest human sensitivity to arrive at a single number which describes the vibration intensity. Portable ride meters have been developed to provide expedient field measurements of both Absorbed Power and the ISO accelerations.

2. In 1978, a NATO working group on mobility composed of representatives from the United States, Canada, France, the Federal Republic of Germany, the Netherlands, and the United Kingdom adopted the Army Mobility Model (AMM) to provide a standardized reference for determining vehicle mobility performance. Upon its adoption, the AMM was subsequently termed the NATO Reference Mobility Model (NRMM). The ride-limiting speed relations customarily used in NRMM are based on Absorbed Power limits (although other limits could readily be used). The use of Absorbed Power instead of the ISO method to describe effects of vehicle vibrations on drivers has caused resistance and concern among both the US and European participants. The United States and its NATO partners in mobility studies need agreed-upon, accepted standards to describe the various aspects of ride quality in meaningful terms for defining the vibrational effects on human health, safety, and performance of military tasks.

3. In December 1983, the Future Armored Vehicle Research (FAVR) Coordinating Committee made up of representatives from the United States and Federal Republic of Germany (US/GE) directed the establishment of a US/GE Expert Group to develop more acceptable and valid measures of ride quality. The work of the Expert Group is a cooperative effort among representatives of the US Army Engineer Waterways Experiment Station (WES), US Army Tank-Automotive

Command (TACOM), the Human Engineering Laboratory (HEL), and the Erprobungsstelle 41 der Bundeswehr Trier (Trier Proving Grounds) in the Federal Republic of Germany. The work of this group would be accomplished under the purview of FAVR Action Team 1 entitled "Mathematical Modeling and Computer Simulations of Vehicle Dynamics and Weapon Stabilization Systems." The members of this Expert Group are:

Mr. Newell R. Murphy, Jr., Co-Chairman	WES
Dr. Dieter Wiegand, Co-Chairman	Trier
Mr. Bobby Reed	WES
Mr. Peter W. Haley	TACOM
Mr. Cedric Mousseau	TACOM
Mr. Andrew Eckles	HEL
Ms. Monica Glum	HEL

4. Because of its relation to the mobility research mission at WES and its importance to the Army, the WES involvement was funded and accomplished under an In-House Laboratory Independent Research (ILIR) project.

Absorbed Power

5. In 1968, the WES, in conjunction with development and validation of AMM, embarked on a comprehensive ride dynamics research and development program. The principal objective was to develop means for predicting ride-limiting speeds of vehicles as a function of terrain roughness. This required a quantitative measure of vehicle vibration levels that were acceptable to humans. WES adopted a promising measure called Absorbed Power, a quantity reflecting the rate at which vibrational energy is absorbed by a typical human, which had just been developed at the TACOM (1). Absorbed Power is conceptually a scalar quantity. Total response can be determined by directly summing absorbed powers in three orthogonal directions; vertical, fore-and-aft, and side-to-side.

6. Since 1968, WES has conducted field ride and shock tests with many types of wheeled and tracked vehicles in terrains throughout the world. Absorbed Power has worked well in defining ride-limiting speeds. Six watts of vertical Absorbed Power was chosen as an upper bound that will permit crew members to effectively perform their tasks. Beyond the 6-watt limit, a

vehicle occupant can do little else except hold tight. Figure 1 illustrates steady state sinusoidal acceleration intensities as a function of frequency that result in 6 watts of Absorbed Power (vertical). Visceral resonances occur in the range of frequencies from 4 to 5 Hz. Tests have shown that highly competitive drivers and crew members will regularly accept Absorbed Power levels ranging up to 10, 20, or more watts for periods up to 10 or 12 minutes (2). These high Absorbed Power conditions, however, frequently caused minor injuries and bruises and often produced vehicle damage, accidents, and cargo damage. Thus, it is recognized that the 6-watt level is not an absolute human tolerance limit and that crew members will, if necessary, risk considerably higher levels of injury and vehicle and cargo damage. Other tests have shown, however, that often only a small increase in speed can be gained by going from 6 watts to 15 or 20 watts. The 6-watt level often occurs when the vehicle's suspension begins "bottoming out," producing discrete shock loads and accelerations in excess of 1 g (where the occupant tends to leave the seat). Modest increases in speed beyond this point significantly increase the intensity and frequency of these shock loads, rapidly increasing Absorbed Power. These high Absorbed Power conditions are not considered to be an effective or meaningful measure of basic ride characteristics.

7. Despite the current concern over the use of the 6-watt Absorbed Power level as a ride-limiting criterion, it has served well for many years as a consistent predictor of practical operational limits. It is not a human tolerance limit; competitive drivers and crews will accept considerably higher Absorbed Power levels for short durations, even at the risk of injury, but experience has indicated the 6-watt level is a reasonable indicator of a driver's self-imposed limits in normal operations.

8. Figure 2 shows the relative and cumulative frequency distributions of the vertical Absorbed Power recorded at the driver's seat of a light wheeled vehicle while negotiating two cross-country mobility traverses. These data reflect the same WES driver in the same vehicle. The driver was instructed to drive the well-marked traverses at the fastest safe speed. Factors other than ride, such as slopes, curves, and vegetation, often restricted the speed. However, the percent of total time the driver spent at ride levels above 6 watts was relatively small (3 minutes or 6 percent on one course and 10 minutes or 21 percent on the other). Other experiences confirm that these results are typical for traverses of this length, but for short test courses

and durations (1 minute or less) speeds are generally limited by vehicle control and result in higher levels of Absorbed Power. In any case, for reasonably long durations, the 6-watt level appears to be a driver-preferred limit.

ISO Acceleration

9. In 1974, after a decade of committee deliberations, ISO published a standard for describing human response to whole-body vibrations that was approved by 19 countries including the United States (3). The ISO standard defines numerical limits for exposure to vibrations in terms of weighted root-mean-square (rms) accelerations in the frequency range of 1 to 80 Hz according to three criteria of increasing intensity -- "reduced comfort boundary," "fatigue-decreased proficiency boundary," and the "exposure limit boundary." Figure 3 illustrates ISO recommended limits on sinusoidal acceleration as a function of frequency and exposure time. The preferred method of evaluation is to compare separately each rms acceleration level for 1/3-octave bands of specified center frequencies against the recommended level at each frequency. This procedure assumes that there are no significant interactions between frequencies. An alternate method, which appears to be more appropriate for complex vibrations, sums the weighted accelerations to an overall rms level expressed by a single quantity (4). This single quantity method led to the development of portable ride meters. One such meter was built in the United States in 1978 by Endevco for the Society of Automotive Engineers (SAE) Ad Hoc Ride Meter Task Force in accordance with specifications cited in ISO 2631 and SAE J1013 publications. Today the principal manufacturer of ISO ride meters is Bruel and Kjaer. For vibrations occurring along more than one axis simultaneously, each axis is evaluated separately and vectorially summed. Concern over this method and a number of other deficiencies have been highlighted, most notably the lack of empirical support of the time-dependency relations (5). It has been shown that persons seem to become acclimated to certain types of vibrations and become more willing to accept the vibrations over a period of time, while for other types of vibrations acceptance rapidly decreases with increases in duration of exposure.

10. Over the past 15 years, WES has developed a unique, wide-ranging data base of vertical, horizontal, and rotational acceleration measurements, along with the corresponding human subjective comments and ratings, terrain

measurements, and vehicle characteristics. These data are stored on analog FM magnetic tapes and provide a ready source of substantial information for detailed studies.

Objective

11. The objective of this study is to compare the relative merits of Absorbed Power and ISO root-mean-square acceleration as useful measures of the human vibration environment, and to make a recommendation of one measure to use in the NATO Reference Mobility Model.

Scope of Work

12. Joint US/GE ride quality tests with three tracked and four wheeled vehicles were conducted in June 1984 at the Proving Grounds in Trier. The standard three-axis accelerometer packages used by WES and Trier, respectively, were mounted adjacent to each other on the driver's seat of each vehicle. WES recorded the outputs of the six accelerometers on analog magnetic tape using a portable seven-channel recorder. Similar joint tests are planned in the near future in the United States at WES. In addition, to this limited test program, the two ride quality criteria (Absorbed Power and ISO) were calculated from selected vehicle acceleration data from the WES data base to provide a broader range of conditions. All information will be readily exchanged and thoroughly discussed among FAVR group members. The analysis presented in this report concerns vibration in only the vertical direction. It is recognized that much work needs to be done with the horizontal motions but this is recommended for the follow-on studies.

13. At the conclusion of the Trier tests, WES personnel instructed Trier personnel in the handling and use of the Absorbed Power ride meter and left one ride meter assembly at Trier for use in future tests. WES and Trier personnel exchanged their respective Absorbed Power and ISO weighted acceleration calculations obtained from the test data. In addition to comparing the Absorbed Power and the ISO criteria, the analyses consisted of investigating effects of:

a. location of transducers on the seat

b. analog versus digital processing

c. criteria for vibrational limits

along with a cursory look at the effect of exposure time on acceptance.

PART II: QUANTIFICATION PROBLEMS ASSOCIATED WITH HUMAN VIBRATION LIMITS

Psychological Factors

14. Human reaction to vibration is a complicated dependency upon both physiological (physical) and psychological (mental) disturbances. Absorbed power, ISO acceleration, or any other measure of purely physical motions cannot account for the psychological effects. Even subjective rating definitions deal only with the results of vehicle motions. However, without fail, during driver interviews about short rides rated as very rough, the principal factor causing concern was the perception of incipient loss of vehicle control. Although this does not fit into a motion perception definition, the psychological implications cannot be isolated or removed from the subjective ratings. This psychological influence of vehicle controllability depends strongly on the nature of the vibrations. A ride composed of high-intensity, uniform accelerations will be judged quite differently from one composed of low- to medium-intensity accelerations combined with randomly recurring shock loads. This is a matter of high crest factors; i.e., ratio of maximum peak to rms accelerations where the ISO limits are admittedly questionable. Harsh shock loads can catapult driver and vehicle into the air, inducing momentary pain and possible injury, seriously hindering the driver's capability to control the vehicle. This psychological distinction between uniform motions and motions composed of recurring impulses may be the principal cause of the discrepancies in subjective ratings recorded during vehicle field tests.

15. Low-frequency acceleration predominance is characteristic of most conventional vehicles. Suspensions are customarily tuned to produce a sprung-mass resonance in the frequency range of 1 to 2 Hz and thereby isolate occupants from irritating vibrations in the 4- to 8-Hz (visceral resonance) region. It appears, at least for short duration travel, that drivers are more willing to accept high uniform vibrations in the 4- to 8-Hz range caused by ultra-stiff suspensions rather than endure the recurring harsh jolts that occur from the softer conventional suspensions which tune the major resonances to the 1- to 2-Hz range.

16. This subjective willingness (as well as health implications) may well be reversed for long duration travels, such as occur during operations of

agricultural and earthmoving equipment. This possible contrast between the effects of short- and long-duration vibrations provides a high potential for application of adaptive (adjustable) suspensions.

17. A further factor worth noting is that, for any given level of absorbed power or ISO acceleration, the subjective ratings increase with increases in surface roughness. That is, a 6-watt ride feels rougher on a rough course than it does on a smooth course.

Physical Injury

18. Current ride quality criteria and the associated subjective responses are mainly measures relating to discomfort and not to bodily injury. It is important to distinguish between these and the nonexistent descriptors of health criteria. Lack of health criteria is a serious shortfall. For example, the acceleration spectra for a vehicle tested earlier revealed high-intensity vibrations in the 3- to 5-Hz region. The duration of this particular test was less than 15 seconds and the ride was rated as acceptable by the driver. However, the 3- to 5-Hz region of these predominant vibrations coincides with the region of natural frequencies of vital organs. Exciting their resonances for lengthy periods (the critical time periods are not known) can cause internal physical damage. The evident danger is that bodily harm could result from "acceptable" vibration levels. Simple experiments cannot be conducted to develop the needed health criteria. Such criteria must emerge through findings that show correlations between particular vibration levels and the unusual incidence of physical injuries. One logical starting point in defining safe vibration levels is to determine representative vibration levels of the most basic form of transportation--walking and jogging. One such study has compared the whole-body vibration levels for walking and jogging, with levels when riding earthmoving machinery (6). The results showed that vibration levels from walking and jogging were equal to or greater than those encountered on earthmoving vehicles, and jogging actually produced a low-frequency level greater than the most restrictive ISO limits.

19. The authors translated the acceleration spectra for a fast walk and a jog from that reference to compare directly with those in an 8x8 vehicle judged intolerable by a healthy driver (Figure 4). A complete spectrum is shown for the fast walk, while, for clarity, only the peaks of the jogging

spectrum are shown. The spectra reveal that the principal peaks for a fast walk, a jog, and the vehicle ride occur at a frequency of about 2 Hz. The highest peak while jogging appears to be about twice that during the vehicle ride. The ISO exposure limit boundaries would not permit such an activity for even a 1-minute duration. The peak acceleration from a fast walk is about 80 percent of the corresponding peak produced by an intolerable vehicle ride. According to the ISO guidelines, this intolerable vehicle ride could be maintained for periods in excess of 25 minutes. Both conclusions appear erroneous.

20. The ISO exposure limit boundaries do not adequately portray realistic ride limits. The tolerance to the high vibration levels encountered in walking or jogging may be due (as Barton conjectures in his report) to an acquired tolerance to their own gait and detailed bodily characteristics that is progressively developed by individuals beginning during their first year of life. It may also be that in ambulation, vibrations occur at regular, largely controllable intervals, adjusted through feedback to avoid individual resonances, while in a vehicle the intervals are random, unpredictable, and not subject to fine tuning. The phenomenon of vibration levels encountered during ambulation appears quite different from that in vehicle ride and at this stage offers no clear basis for defining safe vibration levels.

Exposure Time

21. Whenever drivers are instructed to drive as they see fit and yet try to maintain good speeds, they rarely drive at vibration levels which produce Absorbed Power greater than about 6-watts. The occurrence of levels higher than 6-watts is most often the result of "surprises" that is, the unexpected encounters with unseen rough terrain features. Consequently, due to this driver-imposed preference, the 6-watt limit has proved to be a good "operational" criteria. However, we do know from experience that, if necessary, drivers and crews will accept higher absorbed power levels for short durations. Drivers have been seen to tolerate 20 watts for periods up to about 12 minutes. However, they often paid the price with bruises and frequent vehicle breakdowns.

22. Unfortunately, reliable relations between vibration levels and exposure times do not exist, and this includes the proposed ISO boundaries.

The vehicle test previously discussed (ref Figure 4) lasted for less than one minute and produced over 24 watts of Absorbed Power. The test driver said he could not tolerate that ride again and was unwilling to repeat the test. Yet, observing the spectral graph for the vehicle response and the ISO exposure limit boundaries it is seen that according to the ISO criteria he should have been able to endure the ride for about 25 minutes. This is a vivid example of uncertainties in the ISO duration of exposure boundaries. A first-cut idea of appropriate Absorbed Power levels versus exposure times can be obtained from the results shown in Figure 5 in which are shown Absorbed Power and corresponding ISO exposure limit time boundaries. Assuming the ISO and Absorbed Power maximum speed and roughness relations are identical and ISO exposure time limits are valid, it is seen that one might endure a 6-watt level for a period up to two hours (based on the Absorbed Power curve falling slightly less than mid-way between the 1-hour and the 4-hour ISO boundaries). It is further seen that a 12-watt level may be endured for a period between 25 minutes and an hour. Likewise, levels as high as 20 watts may be endured for periods less than 25 minutes. These values correspond reasonably with observations and measurements from field tests and judgment based on numerous experiences. However, based on the high cost of injuries and vehicle breakdowns that tend to result at these high levels, it is recommended that exposure time at 20 watts Absorbed Power be restricted to periods less than 10 minutes.

23. Based on experiences from other programs, a curve, shown in Figure 6, was prepared that describes a first-cut, upper-bound relation between Absorbed Power and exposure time. This curve has not been thoroughly validated and the true relation may turn out to be dependent on vehicle types. However, it should be useful at this stage of development to select appropriate absorbed power levels for evaluating vehicle ride performance when mission profiles are stated that clearly specify exposure times.

PART III: TEST PROGRAM

Test Vehicles

24. Tests were conducted at the Trier Proving Grounds with three tracked and four wheeled vehicles. However, because of the limited test courses and the non availability of cross-country courses, ride data for three wheeled and two tracked vehicles selected from the WES data base representing previous tests in the United States were reprocessed to provide a broader range of test course conditions. The vehicles considered in this analysis are listed below.

Trier		Supplemental	
Tracked	Wheeled	Tracked	Wheeled
Leopard I	Unimog	M60A1	M151 Jeep
Leopard II	MAN (5-ton)	M3 (BRADLEY)	FAV
M113A2	MAN (10-ton)		LAV
	VW Jeep		

Photographs, which were available for all but the VW Jeep, are shown in Figures 7 through 17.

Instrumentation

25. The principal instrumentation consisted of the two types of ride meters which produced Absorbed Power and ISO root-mean-square (rms) acceleration from accelerometers mounted on the driver's seat.

Trier equipment

26. The Trier equipment consisted of a standard battery operated human response vibration meter type 2511 and triaxial seat pad accelerometer type 4322 all manufactured by Bruel and Kjaer (B&K). The accelerometers were piezoelectric (no DC component) mounted in the standard rubber pad in accordance with the ISO specifications. The frequency weighted filters incorporated into the 2511 vibration meter were in agreement with the relevant ISO standards.

WES equipment

27. The WES equipment consisted of a battery operated absorbed power (ABS-PWR) meter with signal conditioning equipment and a triaxial accelerometer package that was taped on the driver's seat just forward of the Trier accelerometer pad. The accelerometers were Kistler servo, force-balance type with variable range limits and damping and a maximum output of five volts. In the standard usage, the range was set to 5 g giving a sensitivity of 1 volt/g and the damping adjusted to give optimum frequency response in the 0 to 400 Hz range. Power was supplied by the 24 volt batteries of the test vehicles. The frequency weighted filters incorporated into the meter were in agreement with those specified by the TACOM. In addition to the absorbed power ride meter, the unfiltered acceleration data from all six accelerometers (B&K and Kistler) were recorded on a seven channel Frequency Modulated (FM) analog tape recorder to allow more detailed processing. Photographs of various aspects of the Trier and WES equipment are shown in Figures 18 through 21.

SAE Endevco meter

28. In mid-1977, at the recommendations of a Ride Meter Task Force appointed by the chairman of the Society of Automotive Engineers (SAE) Joint Seating Subcommittee, Endevco built a compact, portable single channel ride meter which provides a readout of frequency weighted RMS acceleration directly in m/sec^2. The frequency weighting filter incorporated into the meter was in agreement with the specifications provided in SAE J11013, which were the same as the ISO standards. The accelerometer was a piezoresistive type mounted in the standard rubber pad. This meter was loaned to WES through the courtesy of the Kenworth Truck Company and was used at WES to process unfiltered acceleration data from FM magnetic analog tapes to obtain the SAE/ISO frequency weighted rms acceleration.

Test Courses

29. The test courses at Trier consisted of:

a. Gravel course (moderate roughness, 120 m length)

b. Belgian Block (Two courses)

(1) Low roughness section (120 m length)

(2) High roughness section (120 m length)

c. Concrete washboard (mild sine wave with 0.05 m amplitude and 0.6 m period, 215 m length)

d. Secondary road (gravel)

Segments of all but the secondary road course are illustrated in Figures 22 to 25.

30. The test courses for the supplemental tests obtained from the WES data base consisted of cross-country courses ranging from moderate to severe surface roughness. The courses ranged from 121 to 152 meters in length. These courses were located at Vicksburg, Mississippi, Ft. Knox, Kentucky and Aberdeen Proving Ground, Maryland. Representative photographs of these courses are shown in Figures 26 through 28. The surface roughness of each course was established by special calculations from rod and level measurements taken at 0.3 m (1-ft) intervals longitudinally along the total length of the course. Surface roughness is described in terms of rms elevation. Before surface roughness is calculated, the terrain profile is filtered to remove the effects of wavelengths longer than about 18 m (60 ft), which do not influence vehicle ride (7).

Test Procedures

31. Seven vehicles were tested at Trier Proving Ground in West Germany. Two sets of three-directional accelerometers were attached to the driver's seat of each test vehicle and the respective ride meters and supporting instrumentation packages mounted securely to the vehicle structure. For each test course studied, the vehicle was driven at several speeds beginning with a slow speed and increasing thereafter. Maximum speeds were limited either by vibrations deemed intolerable by the driver or safety considerations. An existing database was tapped to obtain similar acceleration time histories for five additional vehicles tested earlier in the United States under known conditions. The procedures were the same as those for the Trier tests except only one set of three-directional accelerometers was attached to the driver's seat. In each test series, the accelerations on the driver seat were converted to Absorbed Power and to ISO acceleration for ride quality comparisons.

PART IV: ANALYSIS PROCEDURES

General Comments

32. Analysis procedures are displayed in Figure 29. Two physical ride meters were used during the field tests at Trier, West Germany. These will be referred to as the ISO ride meter and the ABS-PWR ridemeter, respectively. The first implemented the vibration measure given by ISO 2631 in terms of a root-mean-square acceleration weighted by frequency-dependent multiplying factors. The second implemented the TACOM vibration measure in terms of Absorbed Power.

33. As the meters were being used during field tests, the outputs of the individual accelerometers that developed signals for the meters were recorded on tape. Some time later, these data were played back in a laboratory setting at WES. Numerical models of the ride meters were developed and provided with inputs from digitized acceleration signals played back from the analog tapes. Both the ISO and the ABS-PWR algorithms were used with each acceleration signal source (analog and digital) to provide a comprehensive basis for comparing the vibration measures. Analyses were limited to measures of vibration in the vertical direction.

Numerical Representation of Ride Meters

34. The basic numerical representation of both the ISO and ABS-PWR methods consists in calculating the Fourier spectrum of an acceleration time history, multiplying spectral components by frequency dependent weights and summing across frequency. The representations differ in that the ISO method involves unequal one-third octave bandwidths and uses the linear spectral components directly, while the ABS-PWR method uses equal bandwidths and deals with squared spectral components. Only spectral components whose frequencies were less than 30 Hz were involved in the summation process to simulate the low-pass filters with 30 Hz cutoff frequencies used in series with the accelerometers in the ride meters.

35. The procedure is illustrated in Figure 30, along with the additional computation of the unweighted root-mean-square acceleration.

36. In both cases, the numerical procedure amounts to filtering an accelerometer signal. It is of interest to compare outputs in this context, bearing in mind that the two vibration measures are not dimensionally equivalent. In Figure 31 the procedure outputs corresponding to hypothetical sinusoidal acceleration inputs are displayed with each response normalized by its maximum value to provide comparable dimensionless quantities. The basic similarity of the methods is evident.

Consistency Checks

37. The self-consistency of the responses of the numerical algorithms and the analog ridemeters was studied using 95 field test records of acceleration. For each test, analog absorbed power was compared to numerically-computed absorbed power using analog and digital accelerations from the ABS-PWR accelerometer as input. Similarly, analog ISO acceleration was compared to its numerical counterpart using analog and digital acceleration from the ISO accelerometer as input. Analog quantities were regressed on their numerical counterparts with the knowledge that a regression line with a unity slope and zero intercept would represent perfect correlation. The outcomes are illustrated in Figures 32 and 33 and based on the regression equations are judged to be satisfactory demonstrations that the results of analog and digital computations were similar. The small differences were attributed to sources of error which were traced to the sampling process imposed upon the analog acceleration signal and to differences between the numerical and analog implementations of the 30 Hz low-passfilters.

38. Subsequent tests of consistency and other cross checks were made using a database of 61 tests representing the best of the data obtained during the field test activity at Trier. Data were discarded that were obviously in error due to miscalibrations and operational faults. The 61 tests were regarded as a "cross-consistency" database.

39. It was judged useful to determine the sensitivity of the numerical algorithms to changes in signal source. Of specific interest was the ability to detect differences in response related to accelerometers placed at different locations. This was done by comparing the ISO and ABS-PWR accelerometers as signal sources. The ISO accelerometers are placed in a rubber pad on the

driver's seat directly under the driver's buttocks. The ABS-PWR accelerometers are placed immediately in front of the ISO accelerometers on the front part of the driver's seat. Thus their separation is small and it was of interest to determine computational sensitivity to these positions.

40. Figure 34 shows the results of 61 analyses in which the accelerometer signal sources were switched between the numerical algorithms. The output of the ISO algorithm using the ABS-PWR accelerometer is plotted against the output of the ISO algorithm using the ISO accelerometer. A regression line is illustrated. The departures of the regression line's intercept and slope from zero and unity, respectively, indicate that the difference in signal source is being detected. Figure 35 reverses the order of regression and expresses a similar result. Thus it is seen that the driver sitting on the accelerometer tended to reduce the level of acceleracion.

41. Figures 36 and 37 perform a similar function for the case in which the ABS-PWR algorithm is driven alternately from the ABS-PWR and ISO accelerometers.

42. Another check felt to be necessary was the comparison of ride meter outputs recorded during field tests and outputs from the same ride meters when driven in the laboratory by recordings of their accelerometer inputs. Figure 38 plots recorded ABS-PWR against laboratory ABS-PWR and shows a regression line. The ideal line would pass through the origin and have unity slope. Figure 39 reverses the regression order. Figure 40 and 41 serve the same function for ISO acceleration.

43. These analyses of procedures were necessary to confirm that there were no significant influences due to analog versus digital computations; due to the different types (servo versus piezoelectric) of accelerometers; and due to the recording equipment. These analyses did, however, indicate a small influence between the locations of the accelerometers on the seat. It appears that a human sitting directly on the accelerometers tends to slightly attenuate the vertical acceleration signal.

PART V: RELATIONSHIPS BETWEEN ISO AND ABSORBED POWER

Regression Analysis

44. It was found to be useful to relate the two vibration measures through regressions. For each of the 61 tests constituting the cross-consistency database, the following quantities were determined:

- a. ABS-PWR ride meter output when driven by recorded ABS-PWR accelerometer.
- b. ABS-PWR ride meter output when driven by recorded ISO accelerometer.
- c. ISO ride meter output when driven by recorded ABS-PWR accelerometer.
- d. ISO ride meter output when driven by recorded ISO accelerometer.
- e. Recorded ABS-PWR ride meter output.
- f. Recorded ISO ride meter output.

45. In Figure 42, quantity "a" is regressed against quantity "c" using a power-law model. A similarity to a square-law relationship is apparent. In Figure 43 quantity "b" is regressed against quantity "d". Again, a square-law relationship could be hypothesized. In Figure 44, however, where quantity "e" is regressed against quantity "f", the relationship is more tenuous. This fact is probably another manifestation of the difference in placement of the accelerometers of the two systems. However, this analytical relation between Absorbed Power and ISO acceleration is useful in determining equivalent levels. For example, to answer the question, "About what level of ISO acceleration corresponds to six-watts absorbed power?" Using the expression from Figure 42 this is determined as follows:

$$\text{ABS PWR} = 1.19\ (\text{ISO})^{2.205}$$

$$6 = 1.19\ (\text{ISO})^{2.205}$$

$$(6/1.19)^{1/2.205} = \text{ISO}$$

$$(5.042)^{0.4535} = \text{ISO} = 2.1\ \text{m/sec}^2$$

or using the expression in Figure 43:

$$\text{ABS PWR} = 1.57\ (\text{ISO})^{2.051}$$

$$6 = 1.57\ (\text{ISO})^{2.051}$$

$$(6/1.57)^{0.4876} = \text{ISO} = 1.9\ \text{m/sec}^2$$

Therefore, the average of the two relations states that:

$$\text{6-watts ABS PWR} \approx 2\ \text{m/sec}^2\ \text{ISO}$$

Examining the "trough portion" of the ISO exposure limit boundaries in Figure 4, it is seen that the 2 m/sec^2 level falls near the 1-hr boundary. This exposure time is in agreement with the 6-watt Absorbed Power exposure time limits shown in Figure 6. The agreement between these exposure time relations tends to substantiate the credibility of the Absorbed Power - ISO regression relations. Similar relations can be established for other Absorbed Power - ISO levels.

Rank Correlation Analysis

46. An uncomplicated and distribution-free technique for estimating the correlation between two quantities of interest is provided by Spearman's coefficient of rank correlation. It deals with the ranks of observed variables rather than with their numerical values. Ranks are obtained by sorting the numerical values of each variable in ascending or descending order. Two sets of ranks replace two sets of numerical values. When ranks are paired by common observational conditions, their differences are used to form a coefficient of rank correlation as follows:

$$R = 1 - \frac{6 \sum_{i=1}^{N} d_i^2}{N\ (N^2 - 1)}$$

where

d_i = the difference between the ranks of the i-th pair of values.

N = the total number of value pairs.

R = the coefficient of rank correlation.

47. The range of the coefficient of rank correlation lies between plus and minus one. In subjective terms, the variables are completely uncorrelated at zero, completely correlated at plus one, and completely anti-correlated at minus one. When sufficient observations are available, tests for the quality of this statistic can be made.

48. When applied to the problem of interest here, the quantities being dealt with are values of ABS-PWR and ISO acceleration corresponding to specific field test conditions. In addition, it was of interest to form value pairs from ABS-PWR and unweighted root-mean-square acceleration.

49. An illustration of the computation of the rank correlation coefficient is presented with the following data to determine the strength of the relation between Absorbed Power (A) and ISO acceleration (I).

Computation of Rank Correlation Coefficient

(A) Abs Pwr (Watts)	(I) ISO (m/sec^2)	Rank of A	Rank of I	d	d^2
3.23	1.38	1	1	0	0
5.98	1.74	3	2	1	1
6.63	1.87	4	3	1	1
8.39	2.16	5	5	0	0
15.73	3.78	7	7	0	0
9.84	2.64	6	6	0	0
3.46	1.92	2	4	-2	4
					6

$$R = 1 - \frac{6(6)}{7(49 - 1)} = 0.89$$

It is readily seen that if there are no differences between the corresponding ranks of the two variables then a complete or perfect correlation exists.

50. Using the 61-test database from the Trier tests and a 101-test database from the supplemental tests, observations were first selected for a specified vehicle traversing a specified test course. Each set of specifications allowed from two to fifteen observations to be drawn from the database. (In the few instances where only one observation could be drawn, the analysis was not made. The results of the Trier tests are presented in Table 1. It is seen there that in eighteen opportunities to form a rank correlation coefficient between ABS-PWR and ISO acceleration, seventeen indications of complete correlation result. This outcome suggests that both vibration measures are almost equally effective in characterizing human vibration intensity. It is also seen that fifteen indications of complete correlation are found between ABS-PWR and the unweighted root-mean-square acceleration. This outcome suggests that accelerometers mounted in proximity to the driver's seat have an appreciable capability by themselves to characterize human vibration intensity.

51. The rank correlation results of the supplemental tests, which reflect a broader range of terrain conditions, are presented in Table 2. Three wheeled and two tracked vehicles are represented on a variety of cross-country terrains representing a broad range of surface roughness conditions. Of the sixteen opportunities to form a rank correlation coefficient, fourteen result in a perfect correlation between ABS PWR and ISO and the remaining two cases show high correlation. However, only seven of the sixteen reflect perfect correlation between ABS PWR and the unweighted acceleration and there are several extremely low correlations. Table 3 shows the rank correlation results of the Trier tests where the rank correlation coefficient was based on several vehicles on a specific course. Generally, the relation between ABS PWR and ISO was high except for the wash board course which is extremely frequency dependent. The correlation between ABS PWR and unweighted acceleration was low. Table 4 shows the rank correlation results of the supplemental tests where the rank correlation coefficient was based on a specific vehicle on several courses. Of the four opportunities to form a rank correlation coefficient, the rank correlation coefficient between ABS PWR and ISO acceleration was high ranging from 0.97 to 0.99. However, the correlation between ABS PWR and the unweighted acceleration was considered low with two of the four occurrences yielding coefficients of 0.64 and 0.55.

52. Based on the results of these various evaluations, it appears that Absorbed Power and ISO acceleration provide similar ranking of vehicle ride performance. On the other hand, Absorbed Power and unweighted acceleration do not, in general, correlate well. This fact can be understood in that unweighted acceleration does not emphasize visceral resonances and does not de-emphasize higher frequency components. Table 5 provides a concise summary of the rank correlation results presented in Tables 1-4.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

53. Data based upon the preceding analyses, it is concluded that

<u>a</u>. Although seemingly based on separate lines of though, in practice, both Absorbed Power and ISO root-mean-square acceleration are implemented by filtering an acceleration signal source.

<u>b</u>. The spectral characteristics of the filters are very nearly the same. In view of this fact it is not surprising to learn that the rank correlations of vertical vibration intensities are high, suggesting that Absorbed Power and ISO acceleration are essentially equally effective in characterizing the human vibration environment in the vertical direction.

<u>c</u>. The use of an unfiltered root-mean-square acceleration measure is moderately effective in such a characterization.

<u>d</u>. Absorbed Power and ISO acceleration provide similar ranking of vehicle ride performance.

Recommendations

54. It is recommended that

<u>a</u>. Extensions of the foregoing study to be undertaken to include the effects of side-to-side and fore-and-aft motion dynamics at the driver's seat.

<u>b</u>. A carefully planned testing program be conducted to deal squarely with the difficult-to-quantify factors relating to effects of exposure time and driver psychology. The involvement of personnel trained to deal with human test subjects is important.

<u>c</u>. Unweighted root-mean-square should not be considered as a measure of human vibration intensity in any but the most expedient circumstances.

<u>d</u>. The NATO Reference Mobility Model should continue to use Absorbed Power as human vibration measure until more experience is gained with ISO acceleration.

<u>e</u>. Further studies of ride dynamics should use both vibration measures while experience accumulates with the ISO measure.

<u>f</u>. In the long run, the suitably improved and tested ISO measure should be placed in service exclusively.

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Table 1

Rank Correlation Results of Trier Tests (Specified Vehicle on a Specified Course)

Test No.	(A) Abs Pwr (Rank) Watts	(I) ISO (Rank) m/sec^2	(R) Unweighted Acceleration (Rank) m/sec^2
		10-Ton Man (Wheeled)	
Course: Gravel			
88	(1) 4.38	(1) 1.595	(1) 2.047
89	(2) 7.024	(2) 2.061	(2) 2.508
90	(3) 13.06	(3) 2.862	(3) 3.376
91	(4) 20.49	(4) 3.283	(4) 3.999
		R(A&I) = 1.0	R(A&R) = 1.0
Course: Wash Board			
85	(2) 14.73	(2) 2.892	(2) 5.077
86	(1) 3.417	(1) 1.507	(1) 3.753
		R(A&I) = 1.0	R(A&R) = 1.0
Course: Belgian Block/Smooth			
82	(1) 6.3	(1) 1.978	(1) 2.666
83	(2) 23.98	(2) 4.132	(2) 5.136
		R(A&I) = 1.0	R(A&R) = 1.0
		M113A2 (Tracked)	
Course: Wash Board			
18	(3) 9.641	(2) 1.939	(1) 2.557
19	(4) 11.74	(4) 2.054	(3) 2.865
20	(2) 8.518	(3) 2.029	(2) 2.783
21	(1) 3.847	(1) 1.272	(4) 2.985
		R(A&I) = 0.8	R(A&R) = 0.4

(Continued)

(Sheet 1 of 5)

Table 1 (Continued)

Test No.	(A) Abs Pwr (Rank) Watts	(I) ISO (Rank) m/sec^2	(R) Unweighted Acceleration (Rank) m/sec^2
M113A2 (Tracked) (Continued)			
Course: Belgian Block/Smooth			
15	(1) 2.461	(1) 1.486	(1) 2.188
16	(2) 5.034	(2) 2.055	(2) 2.844
17	(3) 8.182	(3) 2.609	(3) 3.52
		R(A&I) = 1.0	R(A&R) = 1.0
MAN 5TON (Wheeled)			
Course: Gravel			
27	(1) 0.7697	(1) 0.7703	(1) 1.429
28	(2) 3.563	(2) 1.607	(2) 2.116
29	(3) 7.142	(3) 2.332	(3) 2.934
30	(4) 9.531	(4) 2.799	(4) 3.465
		R(A&I) = 1.0	R(A&R) = 1.0
MAN 5TON (Wheeled) (Continued)			
Course: Belgian Block/Smooth			
23	(1) 1.976	(1) 1.288	(1) 2.113
24	(2) 12.09	(2) 3.19	(2) 4.507
		R(A&I) = 1.0	R(A&R) = 1.0
VWJEEP (Wheeled)			
Course: Gravel			
60	(2) 3.224	(2) 1.756	(2) 2.293
61	(3) 4.37	(3) 2.043	(3) 2.858
62	(4) 4.505	(4) 2.089	(4) 3.003
63	(5) 4.971	(5) 2.310	(5) 3.292
		R(A&I) = 1.0	R(A&R) = 1.0

(Continued)

Table 1 (Continued)

Test No.	(A) Abs Pwr (Rank) Watts	(I) ISO (Rank) m/sec^2	(R) Unweighted Acceleration (Rank) m/sec^2
		VWJEEP (Wheeled) (Continued)	
Course: Belgian Block/Smooth			
57	(1) 4.5	(1) 1.853	(1) 2.541
58	(2) 13.81	(2) 3.355	(2) 4.570
	R(A&I) = 1.0		R(A&R) = 1.0
		LEOPARD I (Tracked)	
Course: Wash Board			
39	(1) 1.394	(1) 0.8837	(1) 1.188
40	(2) 4.286	(2) 1.253	(2) 1.0881
	R(A&I) = 1.0		R(A&R) = 0.5
Course: Smooth Concrete			
49	(1) 0.1354	(1) 0.3585	(2) 0.8253
50	(2) 0.1389	(2) 0.3719	(1) 0.8149
51	(3) 0.2754	(3) 0.5012	(3) 0.9874
	R(A&I) = 1.0		R(A&R) = 1.0
Course: Belgian Block/Smooth			
41	(1) 0.965	(1) 0.9121	(1) 1.363
42	(2) 1.997	(2) 1.289	(2) 1.848
43	(3) 3.298	(3) 1.575	(3) 2.174
44	(4) 5.094	(4) 1.880	(4) 2.378
	R(A&I) = 1.0		R(A&R) = 1.0

(Continued)

Table 1 (Continued)

Test No.	(A) Abs Pwr (Rank) Watts	(I) ISO (Rank) m/sec^2	(R) Unweighted Acceleration (Rank) m/sec^2
		LEOPARD II (Tracked)	
Course: Wash Board			
79	(2) 2.976	(2) 1.8	(2) 3.283
80	(1) 0.5229	(3) 0.6668	(1) 2.162
	R(A&I) = 1.0	R(A&R) = 1.0	
Course: Smooth Concrete			
64	(1) 0.2446	(1) 0.4436	(2) 1.209
65	(2) 0.3597	(2) 0.6209	(1) 1.125
66	(3) 0.5459	(3) 0.699	(3) 1.257
	R(A&I) = 1.0	R(A&R) = 0.5	
Course: Belgian Block/Smooth			
70	(1) 1.302	(1) 0.98	(1) 1.526
71	(2) 1.795	(2) 1.24	(2) 1.998
72	(3) 2.508	(3) 1.46	(3) 2.071
73	(4) 2.779	(4) 1.59	(4) 2.405
74	(5) 2.809	(5) 1.613	(5) 2.478
	R(A&I) = 1.0	R(A&R) = 1.0	
Course Belgian Block/Rough			
67	(1) 1.633	(1) 1.099	(1) 1.667
75	(2) 1.92	(2) 1.243	(2) 1.985
76	(3) 2.068	(3) 1.364	(3) 2.036
77	(4) 2.916	(4) 1.658	(4) 2.712
78	(5) 3.488	(5) 1.945	(5) 3.348
	R(A&I) = 1.0	R(A&R) = 1.0	

(Continued)

Table 1 (Concluded)

Test No.	(A) Abs Pwr (Rank) Watts	(I) ISO (Rank) m/sec^2	(R) Unweighted Acceleration (Rank) m/sec^2
		UNIMOG (Wheeled)	
Course: Gravel			
4	(1) 2.412	(1) 1.436	(1) 1.873
5	(2) 3.759	(2) 1.804	(2) 2.395
6	(3) 4.443	(3) 2.075	(3) 2.64
	R(A&I) = 1.0		R(A&R) = 1.0
Course: Belgian Block/Smooth			
7	(1) 0.6935	(1) 0.7467	(1) 1.232
8	(2) 6.691	(2) 2.287	(2) 3.48
	R(A&I) = 1.0		R(A&R) = 1.0

(Sheet 5 of 5)

Table 2

Rank Correlation Results of Supplemental Tests

(Specified-Vehicle in a Specific Course)

Test No.	(A) Abs Pwr (Rank) Watts	(I) ISO (Rank) m/sec^2	(R) Unweighted Acceleration (Rank) m/sec^2
	FAV (Wheeled)		
Course: Let No. 6 SFC Roughness = 4.6 cm (1.8 in.)			
167	(1) 3.55	(1) 1.07	(1) 1.90
169	(2) 10.12	(2) 1.81	(2) 3.19
171	(3) 19.23	(3) 2.70	(3) 4.74
174	(4) 30.29	(4) 3.19	(4) 5.70
177	(5) 55.10	(5) 4.56	(5) 8.45
	R(A&I) = 1.0	R(A&R) = 1.0	
Course: Let No. 7 SFC Roughness = 7.1 cm (2.8 in.)			
179	(1) 4.58	(1) 1.67	(1) 2.12
180	(2) 4.70	(2) 1.74	(2) 2.27
181	(4) 15.54	(4) 3.21	(4) 4.16
182	(3) 13.71	(3) 3.01	(3) 3.99
183	(5) 24.53	(5) 4.20	(6) 5.62
184	(6) 24.66	(6) 4.22	(5) 5.56
185	(7) 30.04	(7) 4.65	(7) 6.01
186	(8) 30.55	(8) 4.82	(8) 6.17
187	(9) 42.67	(9) 5.59	(9) 7.35
188	(10) 55.88	(10) 6.42	(10) 8.70
	R(A&I) = 1.0	R(A&R) = 0.99	
Course: Let No. 5 SFC Roughness = 4.0 cm (1.6 in.)			
150	(2) 3.30	(2) 1.36	(2) 1.76
157	(1) 3.09	(1) 1.35	(1) 1.72
152	(4) 10.84	(4) 2.55	(4) 3.19
153	(3) 9.18	(3) 2.43	(3) 3.02
154	(6) 16.78	(6) 3.41	(6) 4.22

(Continued)

Table 2 (Continued)

Test No.	(A) Abs Pwr (Rank) Watts	(I) ISO (Rank) m/sec^2	(R) Unweighted Acceleration (Rank) m/sec^2
	FAV (Wheeled) (Continued)		
Course: Lat No. 5 (Continued) SFC Roughness = 4.0 cm (1.6 in.)			
155	(5) 16.12	(5) 3.23	(5) 4.02
156	(8) 24.10	(8) 4.19	(8) 5.24
157	(7) 22.24	(7) 3.90	(7) 4.98
158	(11) 36.97	(10) 4.84	(10) 6.06
160	(9) 32.04	(9) 4.52	(9) 5.71
161	(14) 45.67	(12) 5.33	(12) 6.61
162	(12) 38.06	(11) 5.10	(11) 6.39
163	(13) 45.39	(14) 6.12	(14) 7.82
164	(10) 35.09	(13) 5.36	(13) 7.33
165	(15) 48.34	(15) 6.65	(15) 9.19
	R(A&I) = 0.97	R(A&R) = 0.97	
	M151 Jeep (Wheeled)		
Course: Lat No. 7 SFC Roughness = 7.1 cm (2.8 in.)			
20	(1) 3.53	(1) 1.16	(1) 2.51
23	(3) 14.09	(3) 2.40	(3) 4.82
25	(7) 29.29	(7) 3.47	(7) 6.28
51	(2) 4.53	(2) 1.30	(2) 2.85
54	(4) 15.35	(4) 2.49	(4) 5.09
55	(6) 22.42	(6) 3.05	(6) 5.55
56	(5) 19.63	(5) 2.89	(5) 5.46
	R(A&I) = 1.0	R(A&R) = 1.0	
Course: Lat No. 5 SFC Roughness = 4.0 cm (1.6 in.)			
589	(2) 5.18	(2) 1.44	(2) 2.84
592	(3) 9.10	(3) 1.85	(3) 3.21
594	(5) 15.41	(5) 2.44	(5) 4.37
607	(1) 4.86	(1) 1.43	(1) 2.75
610	(4) 11.86	(4) 2.12	(4) 3.77
	R(A&I) = 1.0	R(A&R) = 1.0	

(Continued)

Table 2 (Continued)

Test No.	(A) Abs Pwr (Rank) Watts	(I) ISO (Rank) m/sec^2	(R) Unweighted Acceleration, (Rank) m/sec^2
		LAV (Wheeled)	
Course: Let No. 4, SFC Roughness = 3.0 cm (1.2 in.)			
30	(1) 3.76	(1) 1.27	(1) 2.84
31	(3) 17.12	(3) 2.59	(4) 6.17
32	(2) 12.46	(2) 2.27	(2) 5.10
35	(4) 19.71	(4) 2.84	(3) 6.10
	R(A&I) = 1.0	R(A&R) = 0.80	
Course: Let No. 5, SFC Roughness = 4.0 cm (1.6 in.)			
37	(2) 13.28	(2) 2.32	(2) 5.04
38	(1) 3.85	(1) 1.23	(1) 2.73
39	(3) 33.32	(3) 3.63	(3) 7.63
41	(4) 46.13	(4) 4.42	(4) 9.45
	R(A&I) = 1.0	R(A&R) = 1.0	
Course: Let No. 7, SFC Roughness = 7.1 cm (2.8 in.)			
42	(1) 4.22	(1) 1.29	(1) 3.26
43	(3) 24.70	(3) 3.06	(3) 7.23
44	(2) 11.86	(2) 2.22	(2) 5.02
45	(4) 47.87	(4) 4.70	(4) 10.62
	R(A&I) = 1.0	R(A&R) = 0.80	
		M3 Bradley (Tracked)	
Course: Ft. Knox No. 1, SFC Roughness = 1.3 cm (0.5 in.)			
5	(1) 3.23	(1) 1.38	(1) 4.40
6	(3) 5.98	(2) 1.74	(6) 7.08
7	(4) 6.63	(3) 1.87	(2) 5.16

(Continued)

Table 2 (Continued)

Test No.	(A) Abs Pwr (Rank) Watts	(I) ISO (Rank) m/sec^2	(R) Unweighted Acceleration (Rank) m/sec^2
		M3 Bradley (Tracked)	
Course:	Ft. Knox No. 1 (Continued) SFC Roughness = 1.3 cm (0.5 in.)		
8	(5) 8.39	(5) 2.16	(3) 5.76
9	(7) 15.73	(7) 3.78	(7) 7.78
10	(6) 9.84	(6) 2.64	(4) 5.78
11	(2) 3.46	(4) 1.92	(5) 6.13
	R(A&I) = 0.89	R(A&R) = 0.47	
Course:	Ft. Knox No. 2 SFC Roughness = 2.0 cm (0.8 in.)		
18	(1) 0.83	(1) 0.84	(2) 5.25
19	(3) 2.02	(3) 1.22	(5) 6.27
20	(2) 1.56	(2) 1.05	(1) 3.80
21	(4) 3.15	(4) 1.49	(6) 6.65
22	(5) 3.42	(5) 1.50	(4) 6.13
23	(6) 6.00	(6) 2.00	(3) 6.09
	R(A&I) = 1.0	R(A&R) = 0.43	
Course:	Ft. Knox No. 3 SFC Roughness = 2.5 cm (1.0 in.)		
37	(1) 3.30	(1) 1.53	(1) 6.53
38	(2) 3.55	(2) 1.58	(4) 7.12
39	(4) 5.79	(4) 2.04	(8) 8.80
40	(3) 5.42	(3) 1.92	(7) 8.27
41	(5) 7.76	(5) 2.32	(3) 6.97
42	(7) 8.62	(7) 2.42	(2) 6.70
43	(8) 9.99	(8) 2.72	(6) 7.48
44	(6) 8.60	(6) 2.44	(6) 7.24
	R(A&I) = 1.0	R(A&R) = 0.17	
Course:	Ft. Knox No. 4 SFC Roughness = 8.1 cm (3.2 in.)		
54	(2) 15.64	(2) 3.87	(2) 8.38
55	(1) 12.40	(1) 3.51	(1) 8.19

(Continued)

Table 2 (Continued)

Test No.	(A) Abs Pwr (Rank) Watts	(I) ISO (Rank) m/sec^2	(R) Unweighted Acceleration (Rank) m/sec^2
	M3 Bradley (Tracked) (Continued)		
Course:	Ft. Knox No. 4 (Continued) SFC Roughness = 8.1 cm (3.2 in.)		
56	(3) 17.17	(3) 4.23	(3) 8.78
57	(4) 22.54	(4) 4.79	(4) 8.89
	R(A&I) = 1.0	R(A&R) = 1.0	
	M60 Tank (Tracked)		
Course:	APG No. 61 SFC Roughness = 3.8 cm (1.5 in.)		
70	(2) 6.69	(2) 2.30	(2) 7.45
71	(1) 0.65	(1) 0.80	(1) 4.03
72	(4) 16.80	(4) 3.74	(4) 9.00
73	(3) 9.46	(3) 2.68	(3) 7.97
	R(A&I) = 1.0	R(A&R) = 1.0	
Course:	APG No. 57 SFC Roughness = 2.5 cm (1.0 m)		
80	(1) 0.29	(1) 0.52	(1) 3.30
81	(2) 0.46	(2) 0.71	(3) 7.83
82	(5) 1.12	(5) 1.06	(4) 9.19
83	(3) 0.76	(3) 0.88	(2) 5.51
84	(4) 0.77	(4) 0.89	(5) 10.07
	R(A&I) = 1.0	R(A&R) = 0.80	
Course:	APG No. 59 SFC Roughness = 4.8 cm (1.9 in.)		
85	(1) 0.65	(1) 0.79	(1) 3.33
86	(2) 2.06	(2) 1.36	(2) 4.94
87	(3) 6.26	(3) 2.23	(3) 7.16
88	(5) 12.97	(5) 3.38	(4) 7.99

(Continued)

Table 2 (Concluded)

Test No.	(A) Abs Pwr (Rank) Watts	(I) ISO (Rank) m/sec^2	(R) Unweighted Acceleration (Rank) m/sec^2
	M60 Tank (Tracked) (Continued)		
Course:	APG No. 59 (Continued) SFC Roughness = 4.8 cm (1.9 in.)		
89	(4) 8.88	(4) 2.93	(5) 8.05
90	(6) 19.73	(6) 4.18	(6) 9.14
	R(A&I) = 1.0	R(A&R) = 0.95	
Course:	APG No. 63 SFC Roughness = 3.6 cm (1.4 m)		
99	(2) 2.56	(2) 1.51	(4) 7.23
100	(1) 1.43	(1) 1.15	(1) 6.35
101	(3) 3.51	(3) 1.79	(5) 7.40
102	(6) 9.53	(6) 2.79	(6) 7.86
103	(7) 16.26	(7) 3.71	(7) 8.60
104	(4) 4.37	(4) 1.99	(2) 6.63
105	(5) 4.55	(5) 1.99	(3) 7.09
	R(A&I) = 1.0	R(A&R) = 0.71	

Table 3

Rank Correlation Results of Trier Tests

(Several Vehicles on a Specific Course)

Course	Test No.	(A) Abs Pwr (Rank) Watts	(I) ISO (Rank) M/sec^2	(R) Unweighted Acceleration (Rank) M/sec^2
Course: Gravel	88	(8) 4.38	(4) 1.59	(4) 2.04
	89	(12) 7.02	(9) 2.06	(8) 2.50
	90	(15) 13.06	(15) 2.86	(14) 3.37
	91	(16) 20.49	(16) 3.28	(16) 3.99
	27	(1) 0.76	(1) 0.77	(1) 1.42
	28	(5) 3.56	(5) 1.60	(5) 2.11
	29	(13) 7.14	(13) 2.33	(11) 2.93
	30	(14) 9.53	(14) 2.79	(15) 3.46
	59	(2) 1.82	(2) 1.24	(2) 1.50
	60	(4) 3.22	(6) 1.75	(6) 2.29
	61	(7) 4.37	(8) 2.04	(10) 2.85
	62	(10) 4.50	(11) 2.08	(12) 3.00
	63	(11) 4.97	(12) 2.31	(13) 3.29
	4	(3) 2.41	(3) 1.43	(3) 1.87
	5	(6) 3.75	(7) 1.80	(7) 2.39
	6	(7) 4.44	(10) 2.07	(9) 2.64
		R(A&I) = 0.92	R(A&R) = 0.87	
Course: Belgian Block/ Smooth	82	(15) 6.3	(17) 2.66	(5) 1.97
	83	(20) 23.98	(20) 5.13	(18) 4.13
	15	(7) 2.46	(8) 1.48	(10) 2.18
	16	(13) 5.03	(14) 2.05	(15) 2.84
	17	(17) 8.18	(16) 2.60	(17) 3.52
	23	(5) 1.97	(5) 1.28	(8) 2.11
	24	(18) 12.09	(18) 3.19	(19) 4.50
	57	(12) 4.5	(12) 1.85	(14) 2.54
	58	(19) 13.81	(19) 3.35	(20) 4.57
	41	(2) 0.96	(2) 0.91	(2) 1.36
	42	(6) 1.99	(6) 1.28	(4) 1.84
	43	(11) 3.29	(9) 1.57	(9) 2.17
	44	(14) 5.09	(13) 1.88	(13) 2.37
	70	(3) 1.30	(3) 0.98	(3) 1.52
	71	(4) 1.79	(4) 1.24	(6) 1.99
	72	(8) 2.50	(7) 1.46	(7) 2.07
	73	(9) 2.77	(10) 1.59	(11) 2.40
	74	(10) 2.80	(11) 1.61	(12) 2.47
	7	(1) 0.69	(1) 0.74	(1) 1.23
	8	(16) 6.69	(15) 2.28	(16) 3.48
		R(R&I) = 0.99	R(A&R) = 0.88	

(Continued)

Table 3 (Concluded)

	Test No.	(A) Abs Pwr (Rank)	Watts	(I) ISO (Rank)	M/sec^2	(R) Unweighted Acceleration (Rank)	M/sec^2
Course: Smooth Concrete	22	(8)	1.01	(8)	0.77	(5)	1.11
	56	(7)	0.92	(7)	0.73	(4)	0.99
	49	(1)	0.13	(1)	0.35	(2)	0.82
	50	(2)	0.13	(2)	0.37	(1)	0.81
	51	(4)	0.27	(4)	0.50	(3)	0.98
	64	(3)	0.24	(3)	0.44	(7)	1.20
	65	(5)	0.35	(5)	0.62	(6)	1.12
	66	(6)	0.54	(6)	0.69	(8)	1.25
		R(A&I) = 1.0		R(A&R) = 0.5			
Course: Wash Board	85	(10)	14.74	(11)	5.07	(8)	2.89
	86	(4)	3.41	(10)	3.75	(2)	1.50
	18	(8)	9.64	(6)	1.93	(5)	2.55
	19	(9)	11.74	(8)	2.05	(7)	2.86
	20	(7)	8.51	(7)	2.02	(6)	2.78
	21	(5)	3.84	(4)	1.27	(9)	2.98
	25	(11)	22.42	(9)	3.30	(11)	5.31
	39	(2)	1.39	(2)	0.88	(1)	1.18
	40	(6)	4.28	(3)	1.25	(3)	1.88
	79	(3)	2.97	(5)	1.8	(10)	3.28
	80	(1)	0.52	(1)	0.66	(4)	2.16
		R(A&I) = 0.73		R(A&R) = 0.52			

Table 4

Rank Correlation Results of Supplemental Tests

(A Specific Vehicle on Several Courses)

Test No.	(A) Abs Pwr (Rank) Watts	(I) ISO (Rank) M/sec^2	(R) Unweighted Acceleration (Rank) M/sec^2
		M151 Jeep (Wheeled)	
20	(1) 3.53	(1) 1.16	(1) 2.51
23	(7) 14.09	(7) 2.40	(8) 4.82
25	(12) 29.29	(12) 3.47	(12) 6.28
51	(2) 4.53	(2) 1.30	(4) 2.85
54	(8) 15.35	(9) 2.49	(9) 5.09
55	(11) 22.42	(11) 3.05	(11) 5.55
56	(10) 19.63	(10) 2.89	(10) 5.46
589	(4) 5.18	(4) 1.44	(3) 2.84
592	(5) 9.10	(5) 1.85	(5) 3.21
594	(9) 15.41	(8) 2.44	(7) 4.37
607	(3) 4.86	(3) 1.43	(2) 2.75
610	(6) 11.86	(6) 2.12	(6) 3.77
	R(A&I) = 0.99	R(A&R) = 0.96	
		LAV (Wheeled)	
30	(1) 3.76	(2) 1.27	(2) 2.84
31	(7) 17.12	(7) 2.59	(8) 6.17
32	(5) 12.46	(5) 2.27	(6) 5.10
35	(8) 19.71	(8) 2.84	(7) 6.10
37	(6) 13.28	(6) 2.32	(5) 5.04
38	(2) 3.85	(1) 1.23	(1) 2.73
39	(10) 33.32	(10) 3.63	(10) 7.63
41	(11) 46.13	(11) 4.42	(11) 9.45
42	(3) 4.22	(3) 1.29	(3) 3.26
43	(9) 24.70	(9) 3.07	(9) 7.23
44	(4) 11.86	(4) 2.22	(4) 5.02
45	(12) 47.87	(12) 4.70	(12) 10.62
	R(A&I) = 0.99	R(A&R) = 0.98	
		M3 Bradley (Tracked)	
5	(5) 3.23	(4) 1.38	(2) 4.40
6	(15) 5.98	(9) 1.74	(19) 7.08
7	(17) 6.63	(11) 1.87	(3) 5.16
8	(19) 8.39	(18) 2.16	(7) 5.76

(Continued)

(Sheet 1 of 3)

Table 4 (Continued)

Test No.	(A) Abs Pwr (Rank) Watts	(I) ISO (Rank) M/sec^2	(R) Unweighted Acceleration (Rank) M/sec^2
	M3 Bradley (Tracked) (Continued)		
9	(28) 15.73	(27) 3.78	(23) 7.78
10	(23) 9.84	(22) 2.64	(8) 5.78
11	(8) 3.46	(14) 1.92	(11) 6.13
18	(1) 0.83	(1) 0.84	(4) 5.25
19	(3) 2.02	(3) 1.22	(13) 6.27
20	(2) 1.[illegible]	(2) 1.05	(1) 3.80
21	(4) 3.14	(5) 1.49	(15) 6.65
22	(7) 3.42	(6) 1.50	(12) 6.13
23	(16) 6.00	(15) 1.97	(10) 6.09
37	(6) 3.30	(7) 1.53	(14) 6.53
38	(9) 3.55	(8) 1.58	(20) 7.12
39	(14) 5.79	(16) 2.04	(28) 8.80
40	(12) 5.42	(13) 1.92	(24) 8.27
41	(18) 7.76	(19) 2.32	(17) 6.97
42	(21) 8.62	(20) 2.42	(16) 6.70
43	(24) 9.99	(23) 2.72	(22) 7.48
44	(20) 8.60	(21) 2.44	(21) 7.24
54	(27) 15.64	(28) 3.87	(27) 8.38
55	(26) 12.40	(26) 3.51	(26) 8.19
56	(29) 17.17	(29) 4.23	(25) 8.78
57	(30) 22.54	(30) 4.79	(29) 8.89
64	(10) 4.26	(10) 1.87	(5) 5.26
65	(11) 4.48	(12) 1.89	(9) 5.96
66	(22) 8.93	(24) 2.76	(18) 7.08
67	(13) 5.70	(17) 2.06	(6) 5.49
68	(25) 11.71	(25) 3.26	(30) 9.22
	R(A&I) = 0.97	R(A&R) = 0.64	
	M60 Tank (Tracked)		
70	(15) 6.69	(15) 2.30	(14) 7.45
71	(4) 0.66	(4) 0.80	(3) 4.03
72	(23) 16.76	(23) 3.74	(23) 9.00
73	(18) 9.46	(17) 2.68	(18) 7.97
74	(16) 7.51	(16) 2.38	(7) 6.55
78	(21) 14.79	(21) 3.63	(15) 7.73
80	(1) 0.29	(1) 0.52	(1) 3.30
81	(2) 0.46	(2) 0.71	(16) 7.83
82	(7) 1.12	(7) 1.06	(25) 9.19
83	(5) 0.76	(5) 0.88	(5) 5.51
84	(6) 0.77	(6) 0.89	(26) 10.07

(Continued)

Table 4 (Concluded)

Test No.	(A) Abs Pwr (Rank) Watts		(I) ISO (Rank) M/sec^2		(R) Unweighted Acceleration (Rank) M/sec^2	
			M60 Tank (Tracked) (Continued)			
85	(3)	0.65	(3)	0.79	(2)	3.33
86	(9)	2.06	(9)	1.36	(4)	4.94
87	(14)	6.26	(14)	2.23	(10)	7.16
88	(20)	12.97	(20)	3.38	(19)	7.99
89	(17)	8.80	(19)	2.93	(20)	8.05
90	(25)	19.73	(26)	4.18	(24)	9.14
93	(26)	20.14	(25)	4.10	(13)	7.44
99	(10)	2.56	(10)	1.51	(11)	7.23
100	(8)	1.43	(8)	1.15	(6)	6.35
101	(11)	3.51	(11)	1.79	(12)	7.40
102	(19)	9.53	(18)	2.79	(17)	7.86
103	(22)	16.26	(22)	3.71	(21)	8.60
104	(12)	4.37	(13)	1.99	(8)	6.63
105	(13)	4.55	(12)	1.98	(9)	7.09
106	(24)	18.86	(24)	3.85	(22)	8.88

R(A&I) = 0.996   R(A&R) = 0.553

(Sheet 3 of 3)

Table 5

Summary of Rank Correlation Results

Vehicle	Course	Rank Correlation Coefficient AP - ISO	Rank Correlation Coefficient AP-Unwgt
	I. Specific Vehicle on a Specific Course		
	Trier Tests		
Man 10-Ton	Gravel	1.00	1.00
	Wash Board	1.00	1.00
	Belgian Block (Smooth)	1.00	1.00
M113A2	Wash Board	0.80	0.40
	Belgian Block (Smooth)	1.00	1.00
Man 5-Ton	Gravel	1.00	1.00
	Belgian Block (Smooth)	1.00	1.00
VW Jeep	Gravel	1.00	1.00
	Belgian Block (Smooth)	1.00	1.00
Leopard I	Wash Board	1.00	1.00
	Smooth Concrete	1.00	0.50
	Belgian Block (Smooth)	1.00	1.00
Leopard II	Wash Board	1.00	1.00
	Smooth Concrete	1.00	0.50
	Belgian Block (Smooth)	1.00	1.00
	Belgian Block (Rough)	1.00	1.00
Unimog	Gravel	1.00	1.00
	Belgian Block (Smooth)	1.00	1.00
	Supplemental Tests		
FAV	Lat No. 6	1.00	1.00
	Lat No. 7	1.00	0.99
	Lat No. 5	0.97	0.97
M151 Jeep	Lat No. 7	1.00	1.00
	Lat No. 5	1.00	1.00
LAV	Lat No. 4	1.00	0.80
	Lat No. 5	1.00	1.00
	Lat No. 7	1.00	1.00

(Continued)

Table 5 (Concluded)

Vehicle	Course	Rank Correlation Coefficient AP - ISO	AP-Unwgt
	I. Specific Vehicle on a Specific Course		
	Supplemental Tests (Continued)		
M3 Bradley	Ft. Knox No. 1	0.89	0.47
	Ft. Knox No. 2	1.00	0.43
	Ft. Knox No. 3	1.00	0.17
	Ft. Knox No. 4	1.00	1.00
M60 Tank	APG No. 61	1.00	1.00
	APG No. 57	1.00	0.80
	APG No. 59	1.00	0.95
	APG No. 63	1.00	0.71
	II. Several Vehicles on a Specific Course		
-	Gravel	0.92	0.87
-	Belgian Block (Smooth)	0.99	0.88
-	Smooth Concrete	1.00	0.50
-	Wash Board	0.73	0.52
	III. A Specific Vehicle on Several Courses		
M151 Jeep	-	0.99	0.96
LAV	-	0.99	0.98
M3 Bradley	-	0.97	0.64
M60 Tank	-	0.99	0.55

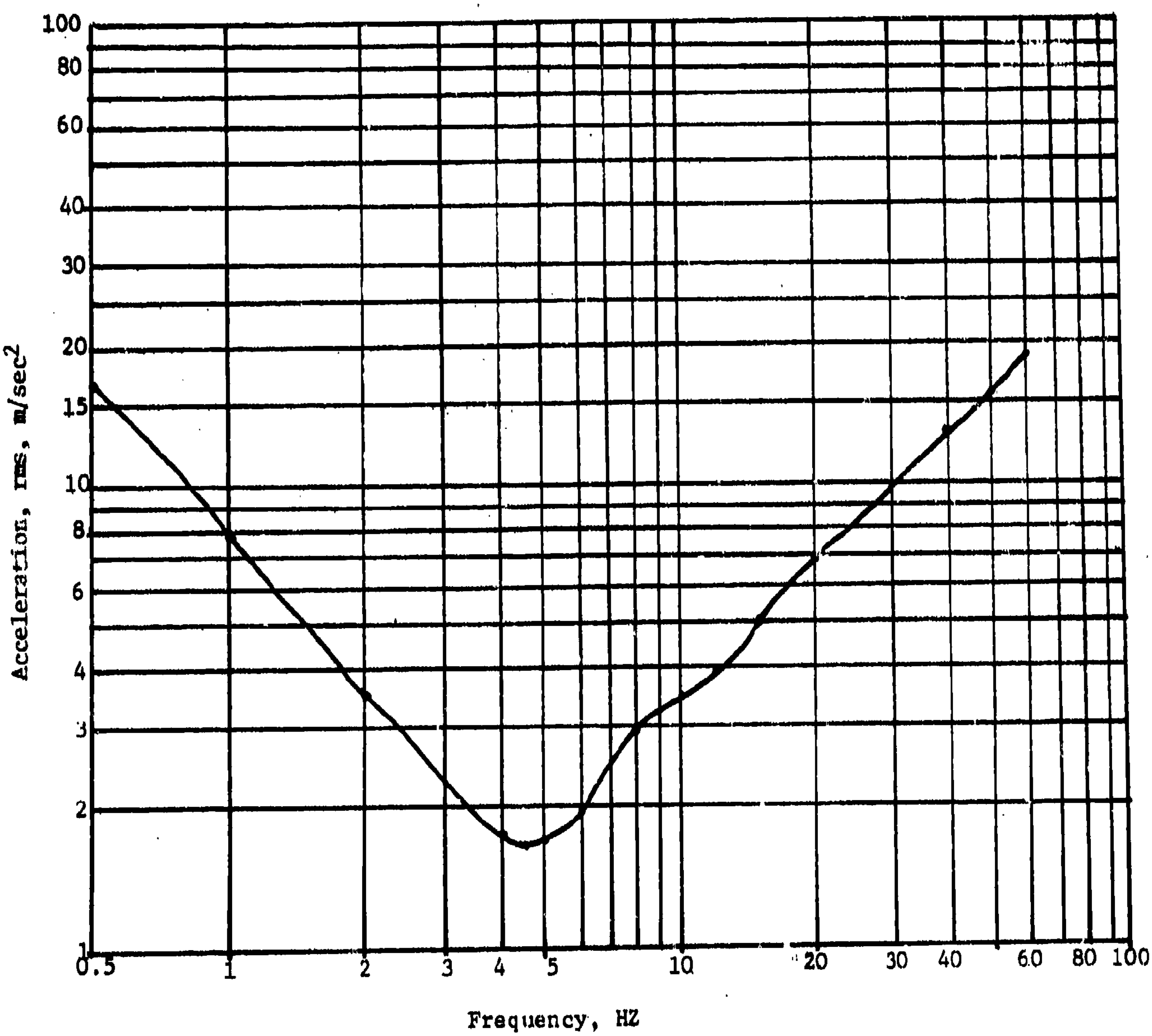


Figure 1. Vertical acceleration-frequency relation for constant 6-watt absorbed power level

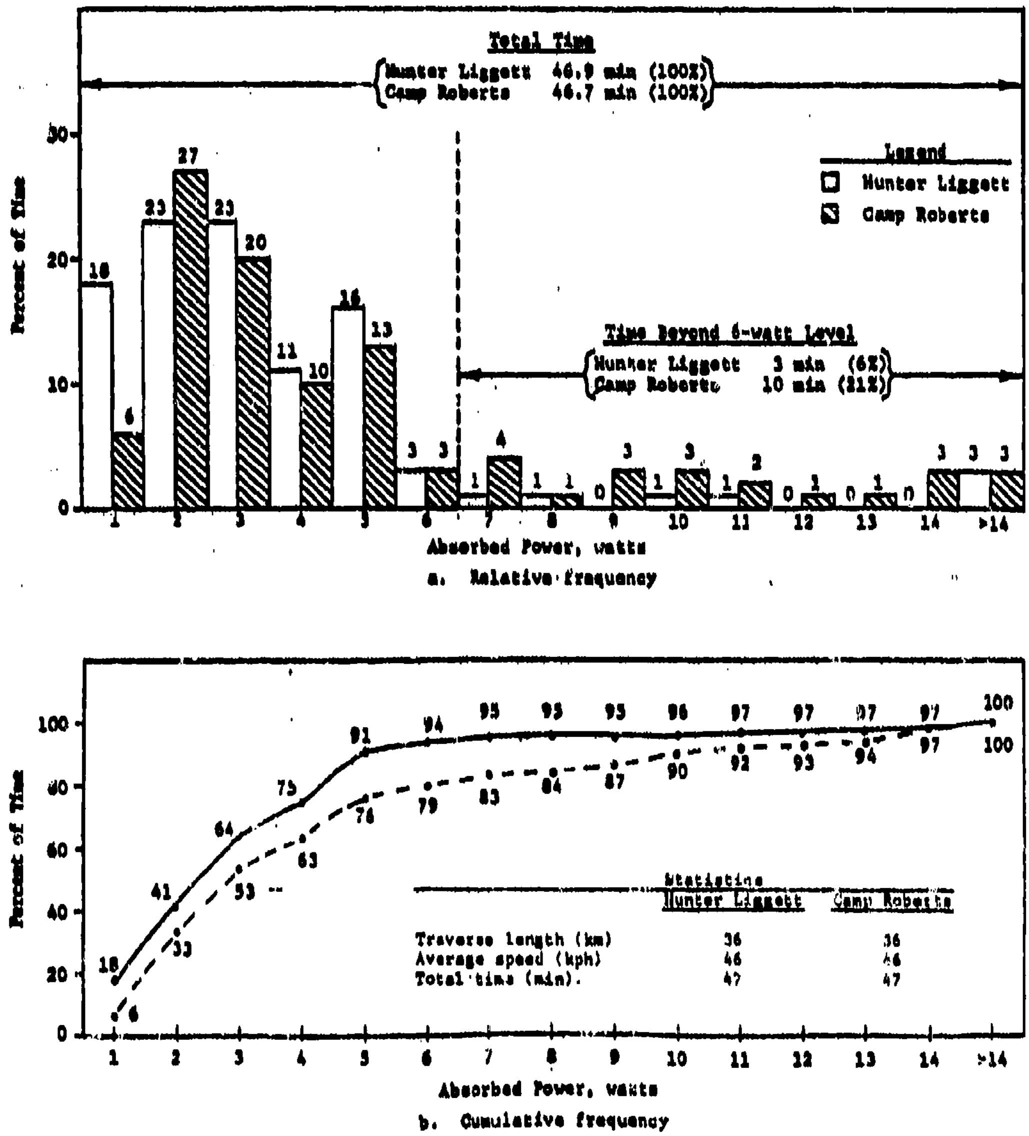


Figure 2. Relative and cumulative frequency distributions of vertical absorbed power measured at the driver's seat of a light wheeled vehicle on two mobility traverses

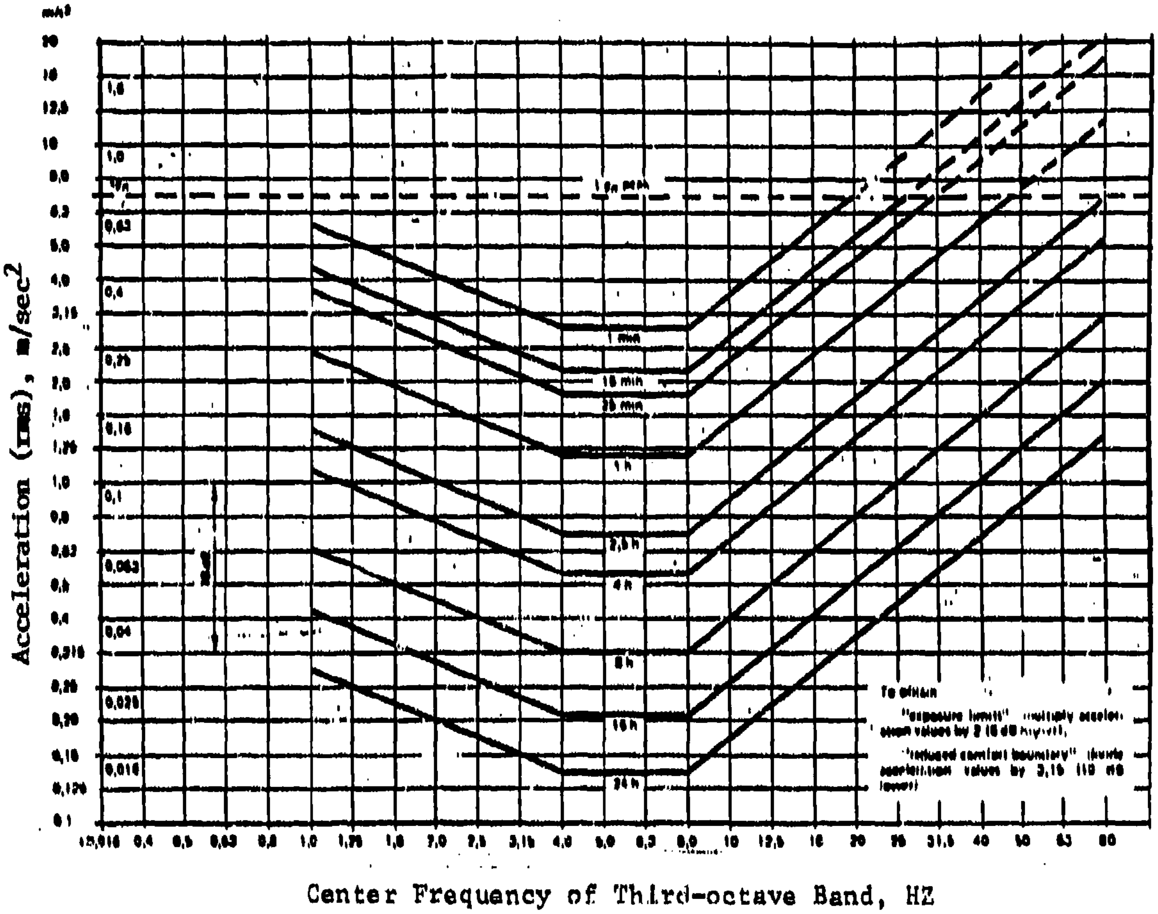


Figure 3. Vertical acceleration limits as a function of frequency and exposure time (fatigue-decreased proficiency boundary)

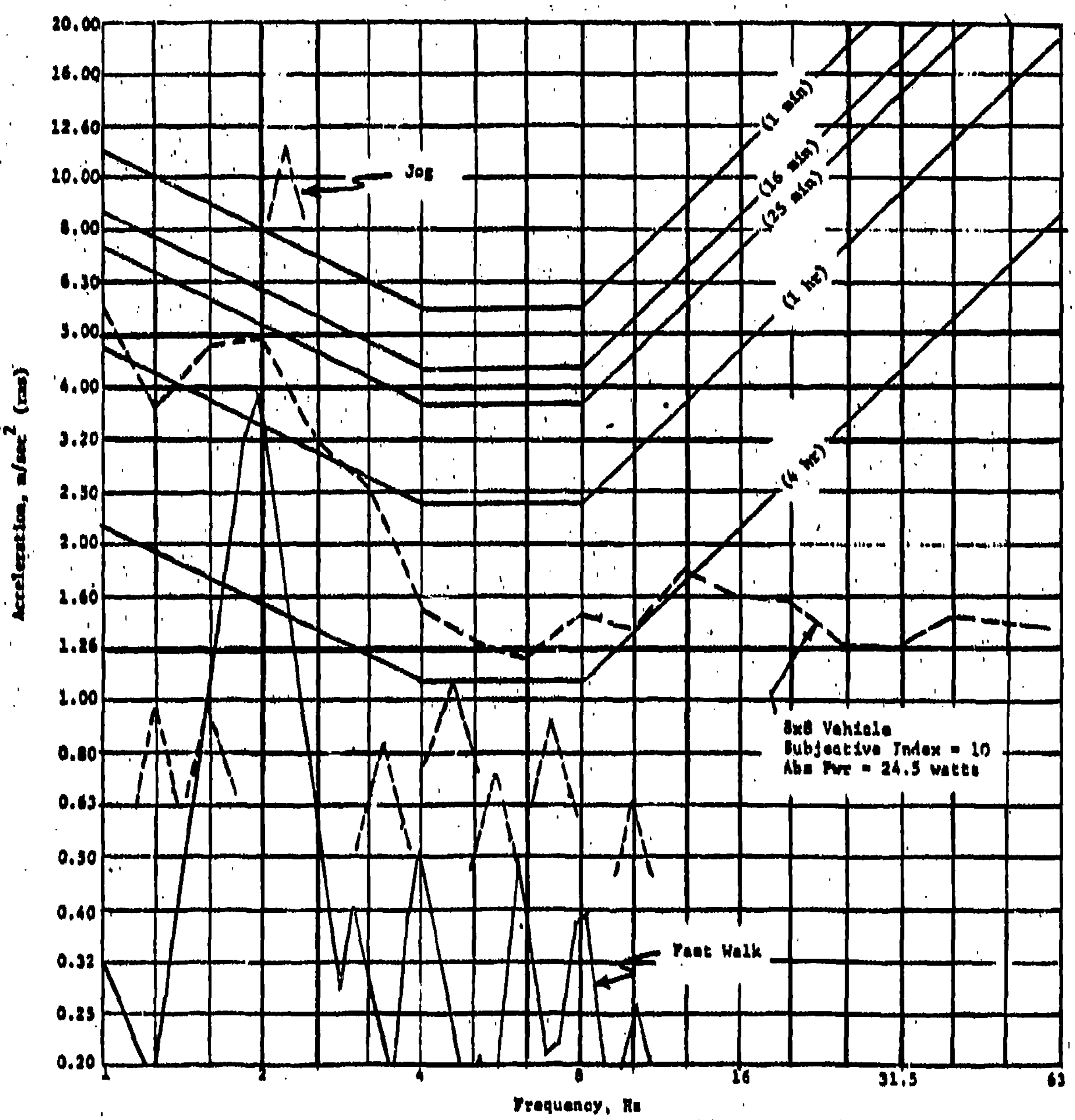
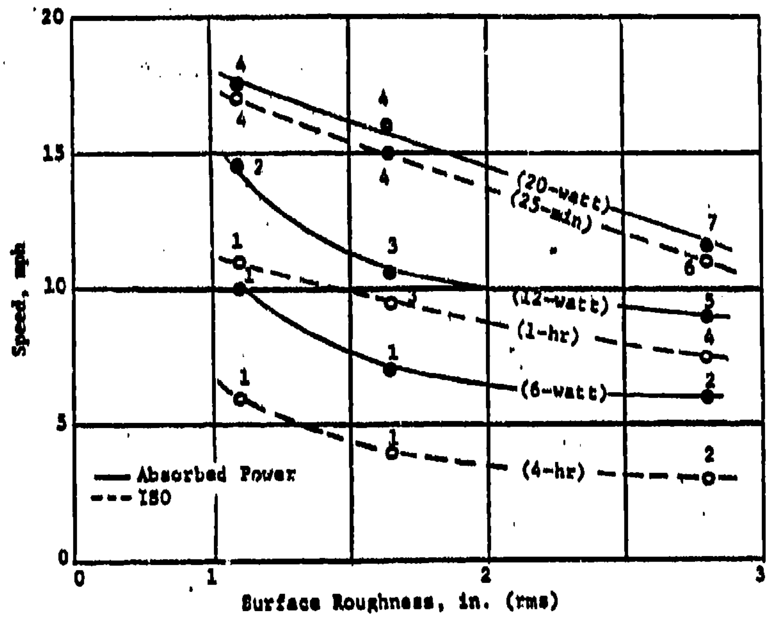


Figure 4. Comparison of vertical acceleration spectra for a fast walk, a jog, and an intolerable ride as judged by a vehicle driver during a ride test in an 8x8 armored vehicle



Subjective Index	Perception
1-2	Barely noticeable
3-4	Strongly noticeable
5-6	Uncomfortable
7-8	Extremely uncomfortable
9-10	Recommended limits (not willing to take for any sustained period of time)

Figure 5. Comparison of absorbed power and ISO limiting-speed versus surface roughness relations for three selected levels of vertical vibrations (ride tests with the 2x4 Dune Buggy).

NOTE: Numbers above data denote driver's subjective rating index.)

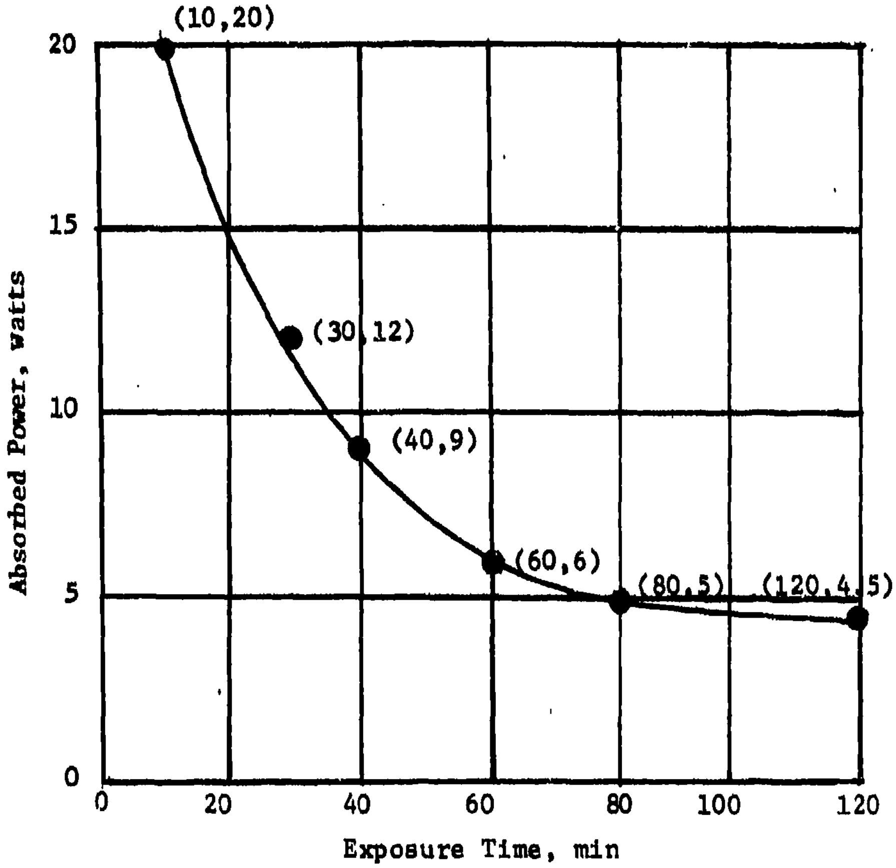


Figure 6. Upper-bound relationship between absorbed power and exposure time

(NOTE: This relation is based on test data but has not been validated)

Figure 7. M151 Jeep

Figure 8. Leopard I

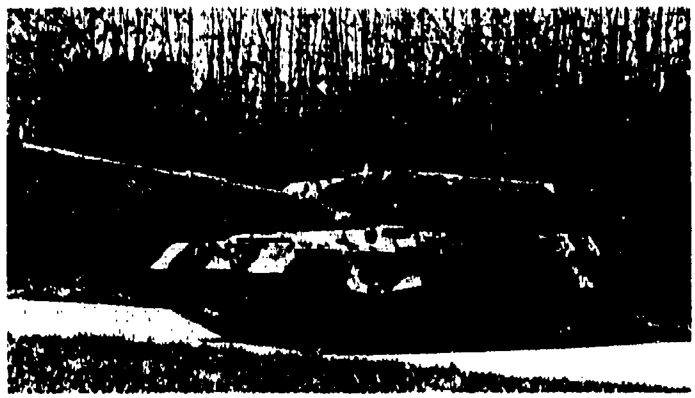


Figure 9. Leopard II

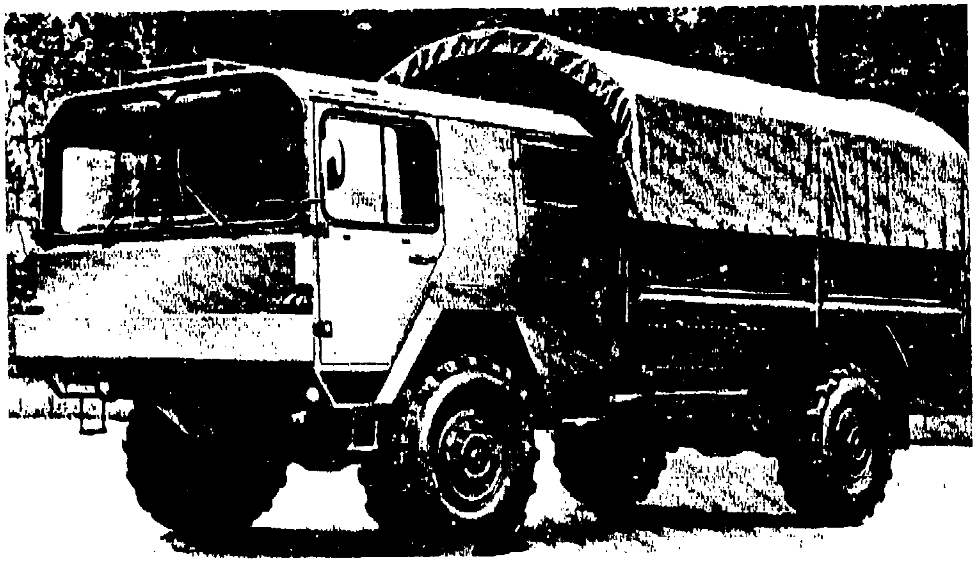


Figure 10. MAN 5-Ton Truck

Figure 1[illegible]. MAN 10-Ton Truck

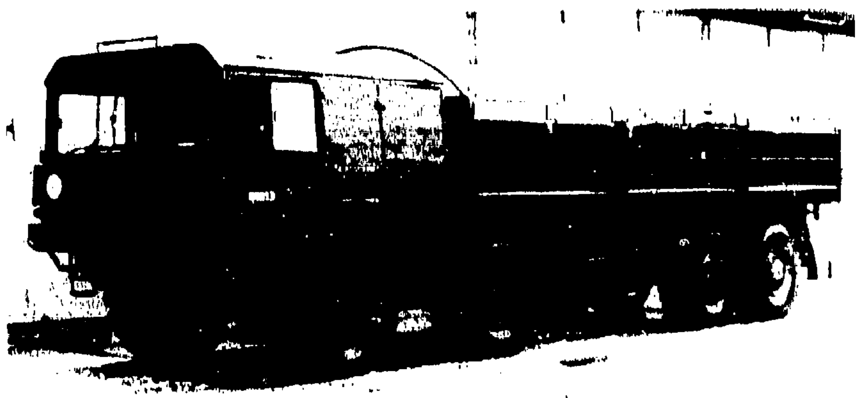


Figure 12. M60A1 Tank

Figure 13. Fast Attack Vehicle (FAV)

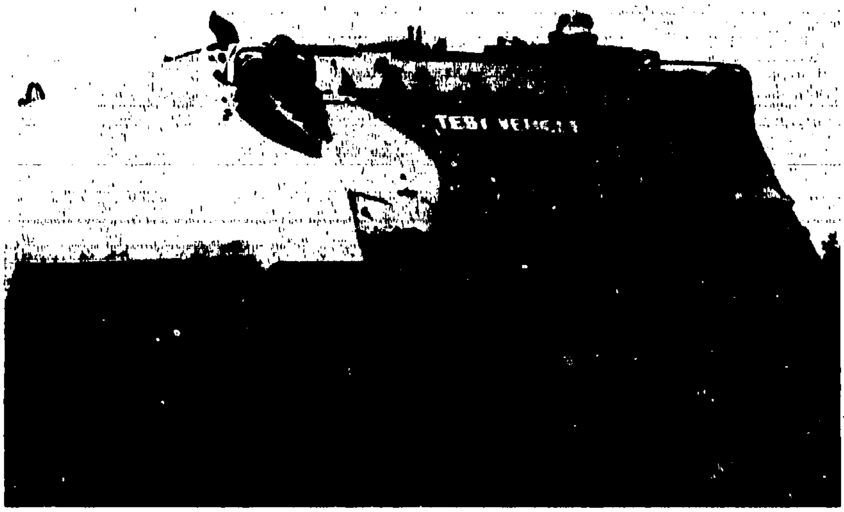
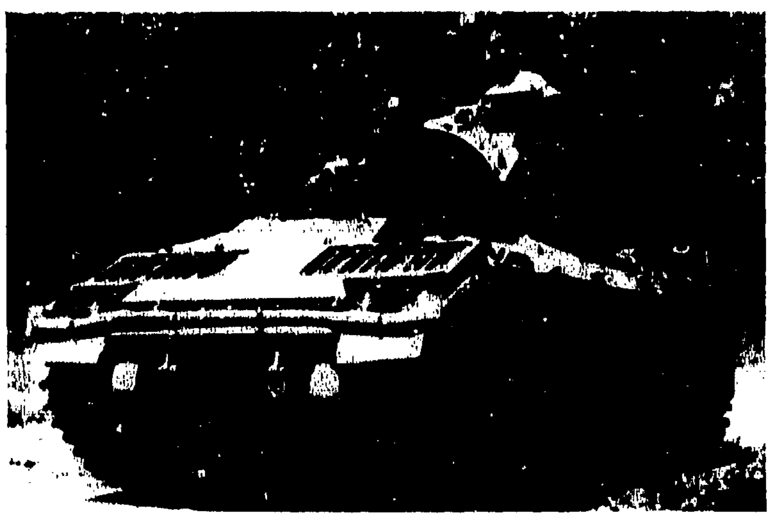


Figure 14. M113A1 Armored Personnel Carrier

Figure 15. M3 Bradley Fighting Vehicle



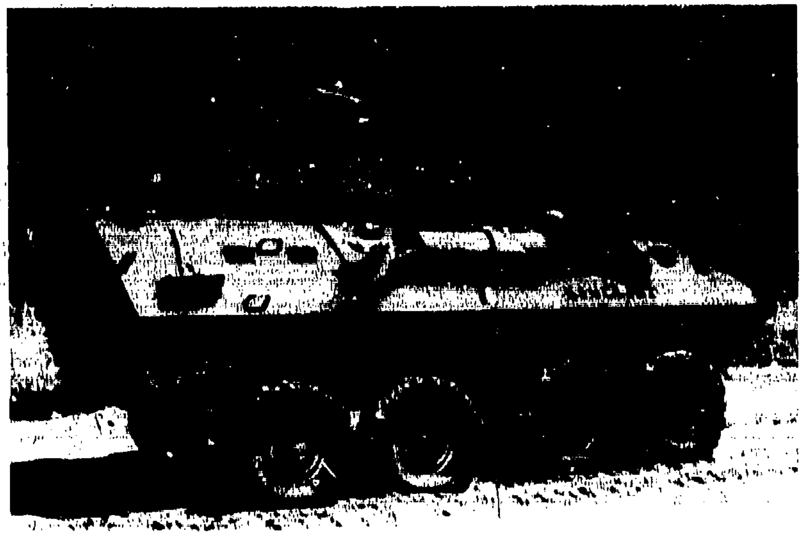


Figure 16. Light Armored Vehicle (LAV)

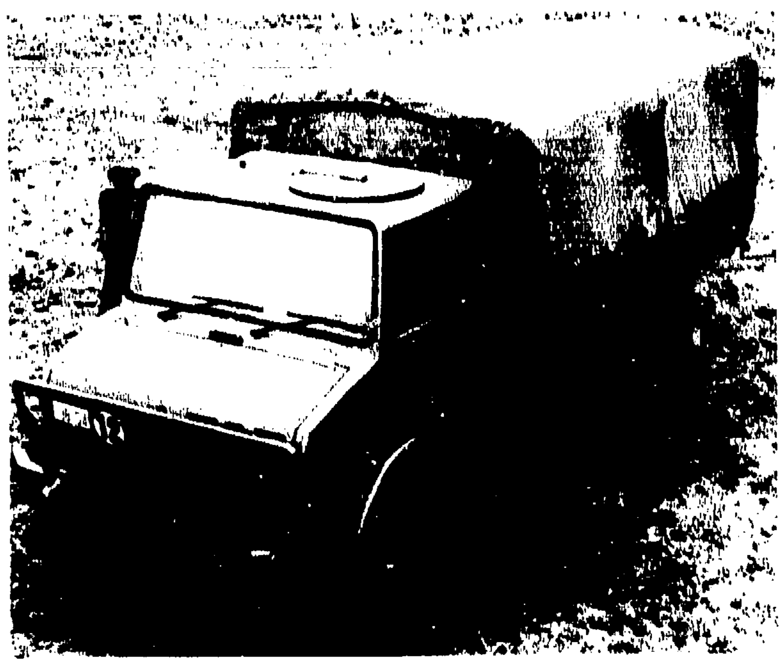


Figure 17. Unimog Utility/Cargo Vehicle

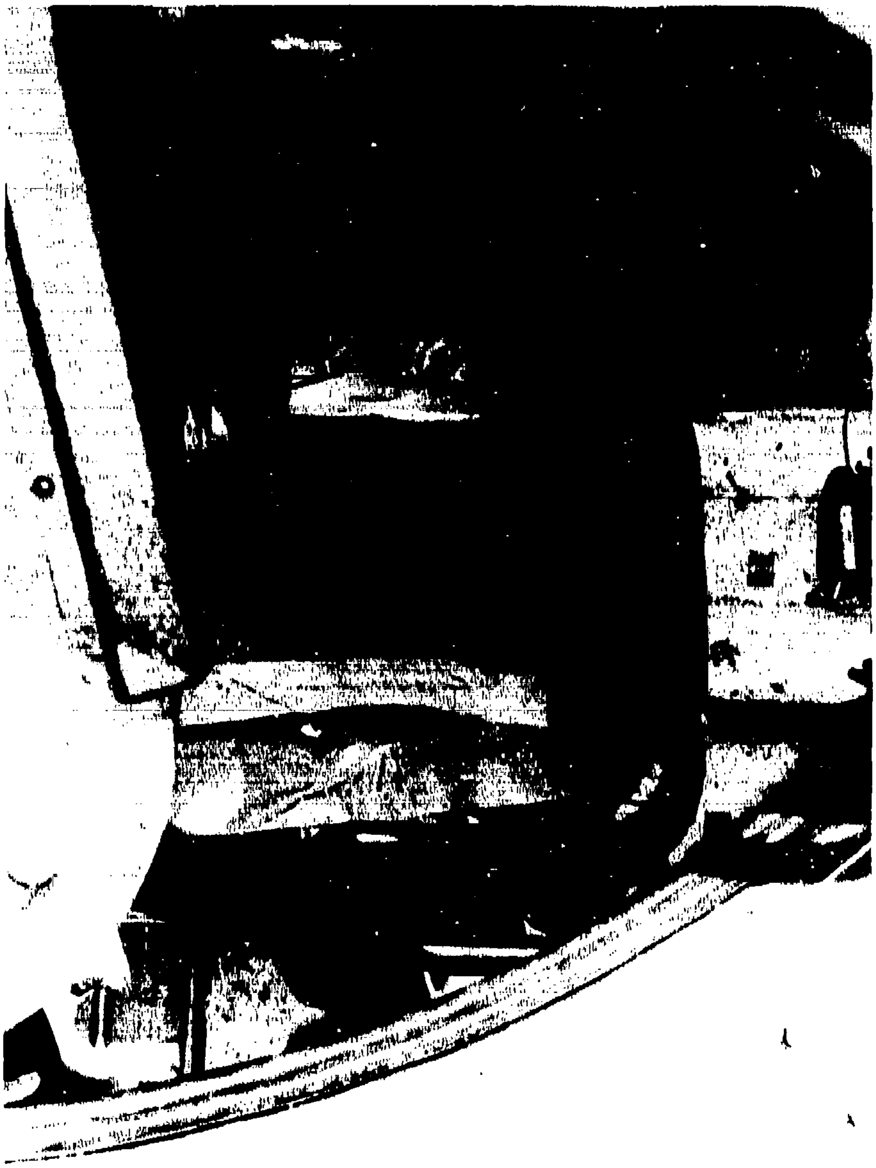


Figure 18. Accelerometers on driver's seat in Leopard II

Figure 19. Accelerometers on driver's seat in Unimog

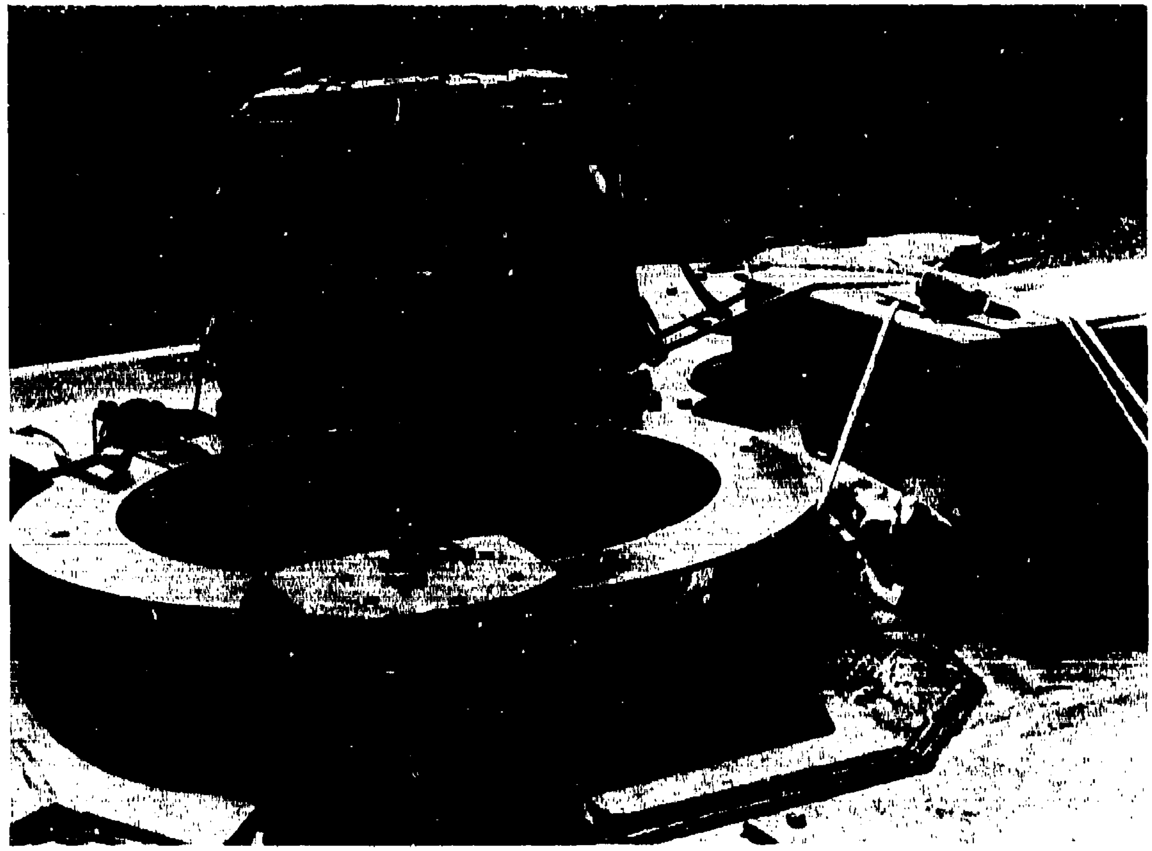


Figure 20. Instrumentation pack placed on Leopard II

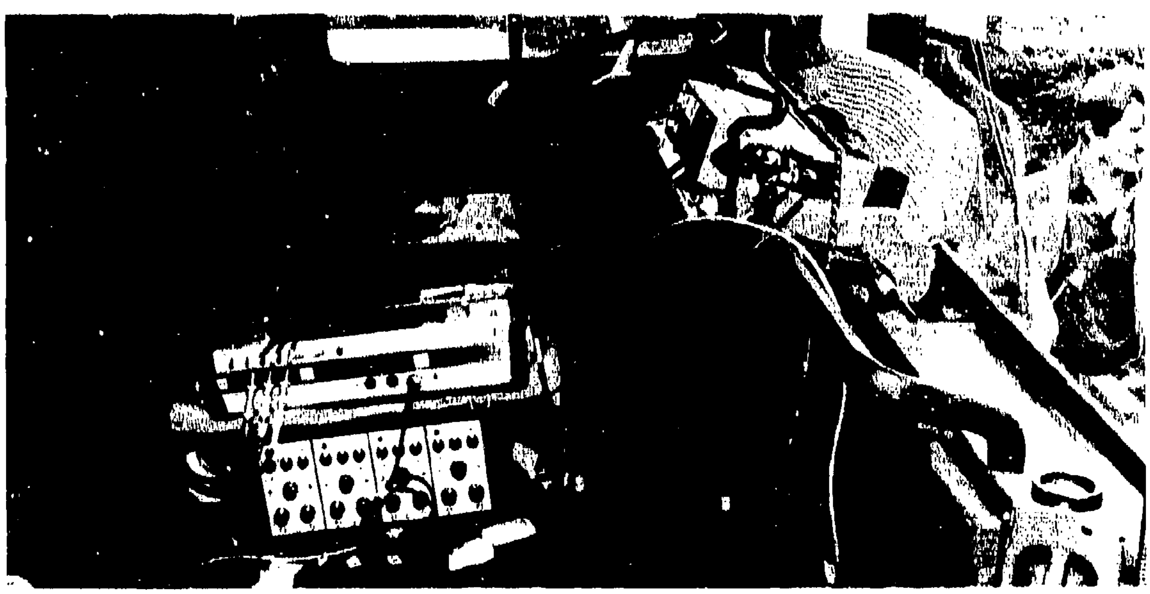


Figure 21. Instrumentation pack placed in MAN 5-Ton

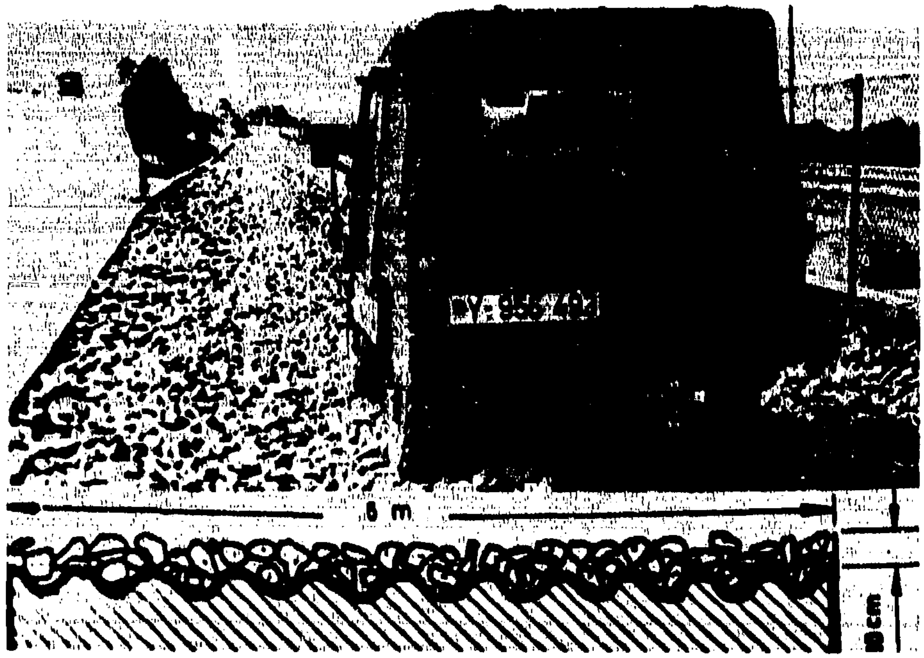


Figure 22. Gravel course at Trier

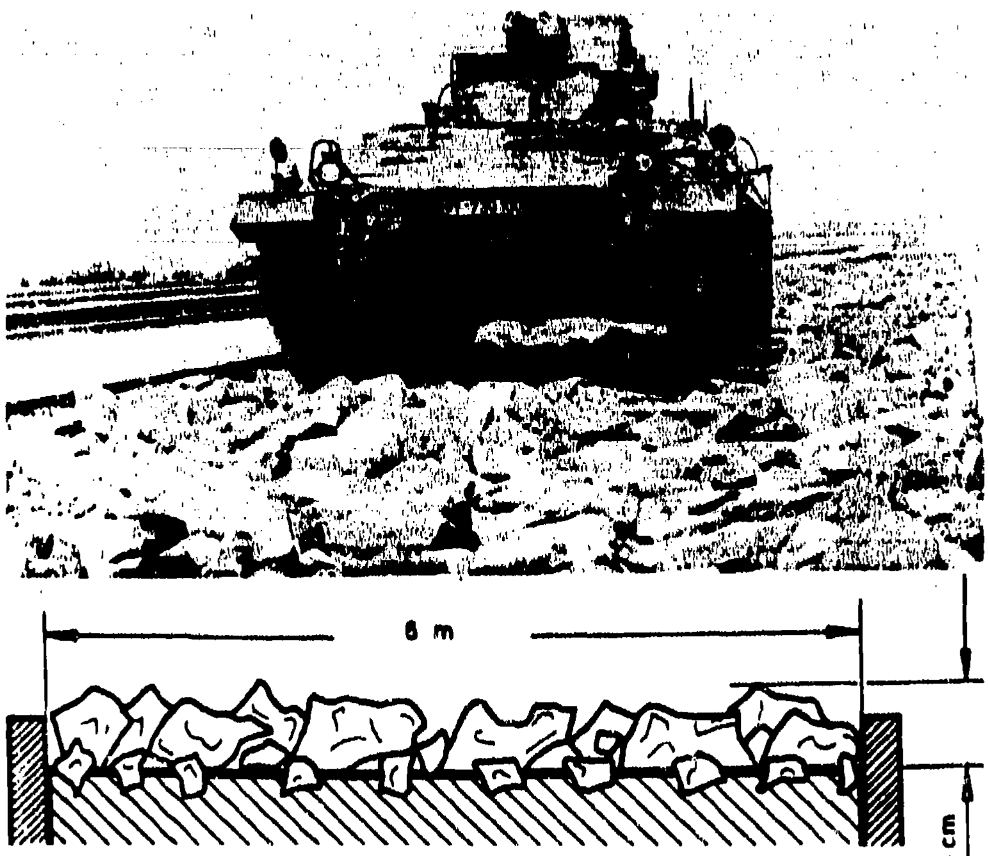


Figure 23. Rough Belgian block course at Trier

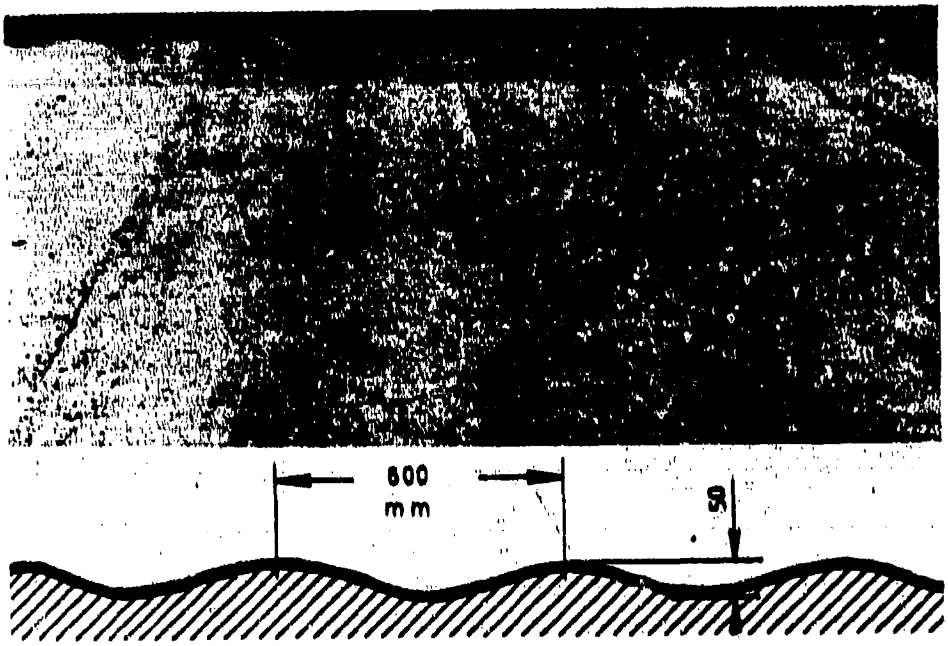


Figure 24. Washboard course at Trier

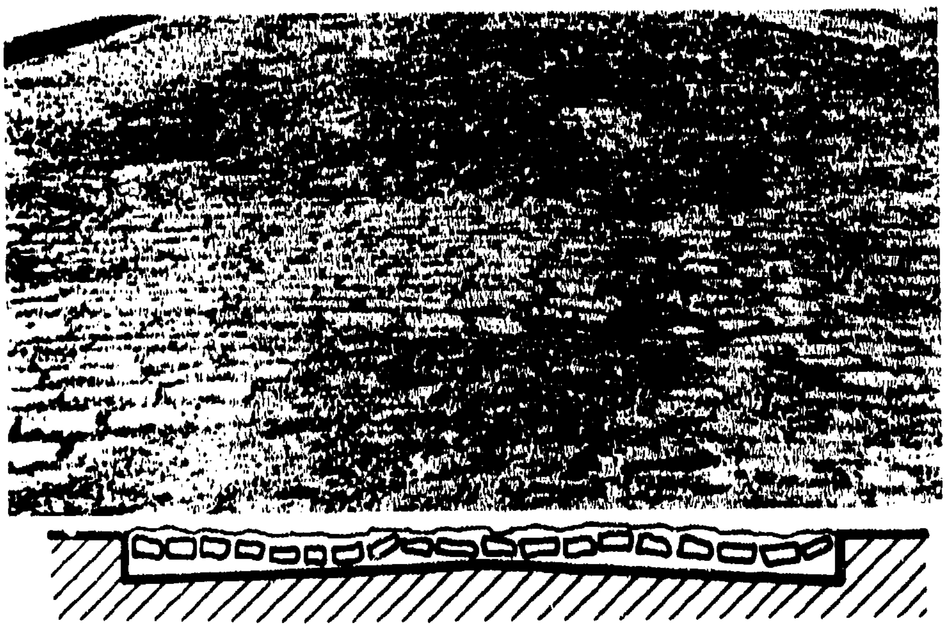


Figure 25. Smooth Belgian block course at Trier

Figure 26. Test course at LeTourneau No. 7, surface roughness = 7.1 (rms), cm

Figure 27. Test course at LeTourneau No. 5, surface roughness = 4.0 (rms), cm

Figure 28. Test course Ft. Knox No. 1, surface roughness = 1.3 (rms), cm

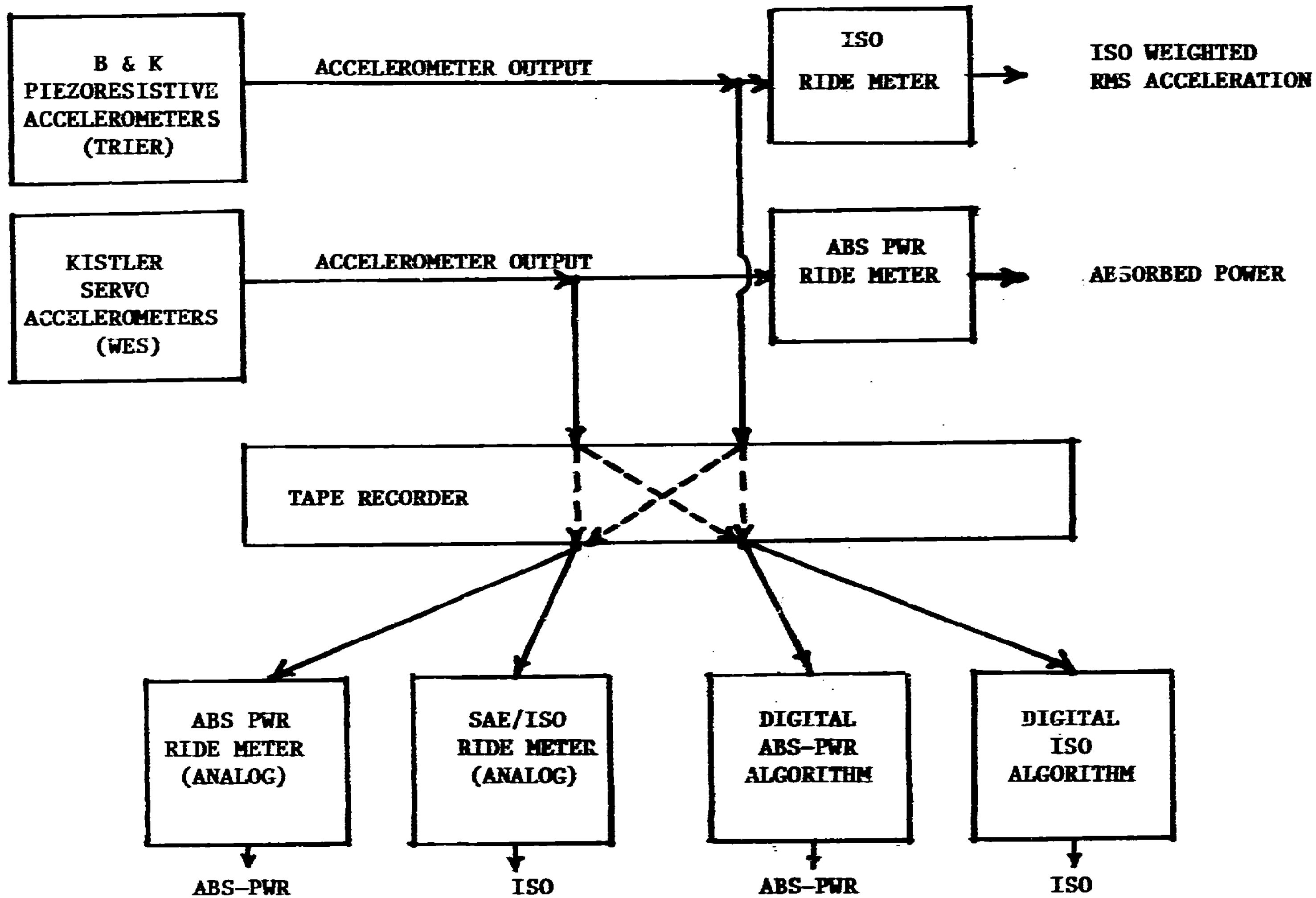


Figure 29. Schematic illustrating basic analysis procedures

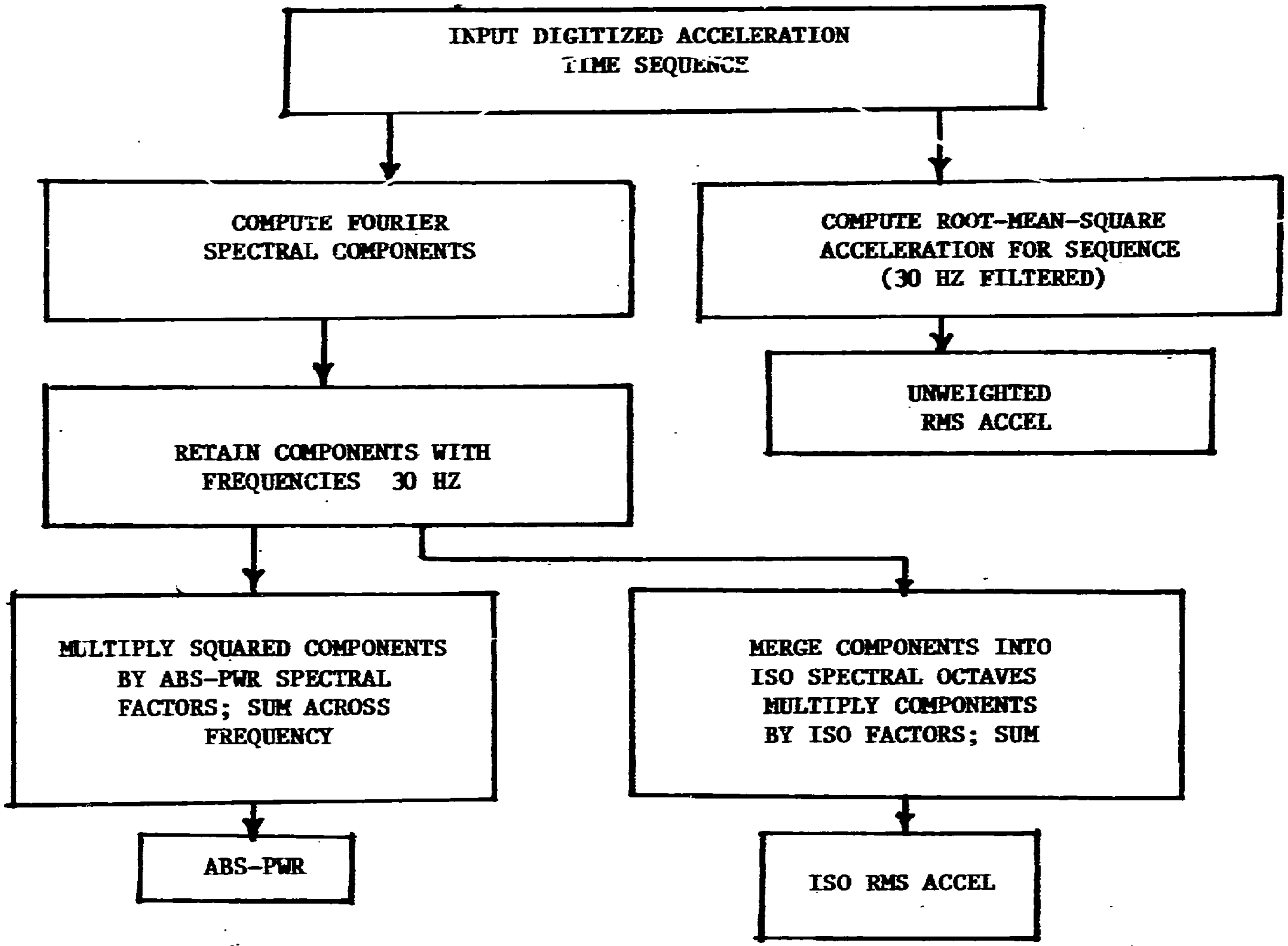


Figure 30. Schematic illustrating numerical computational procedures

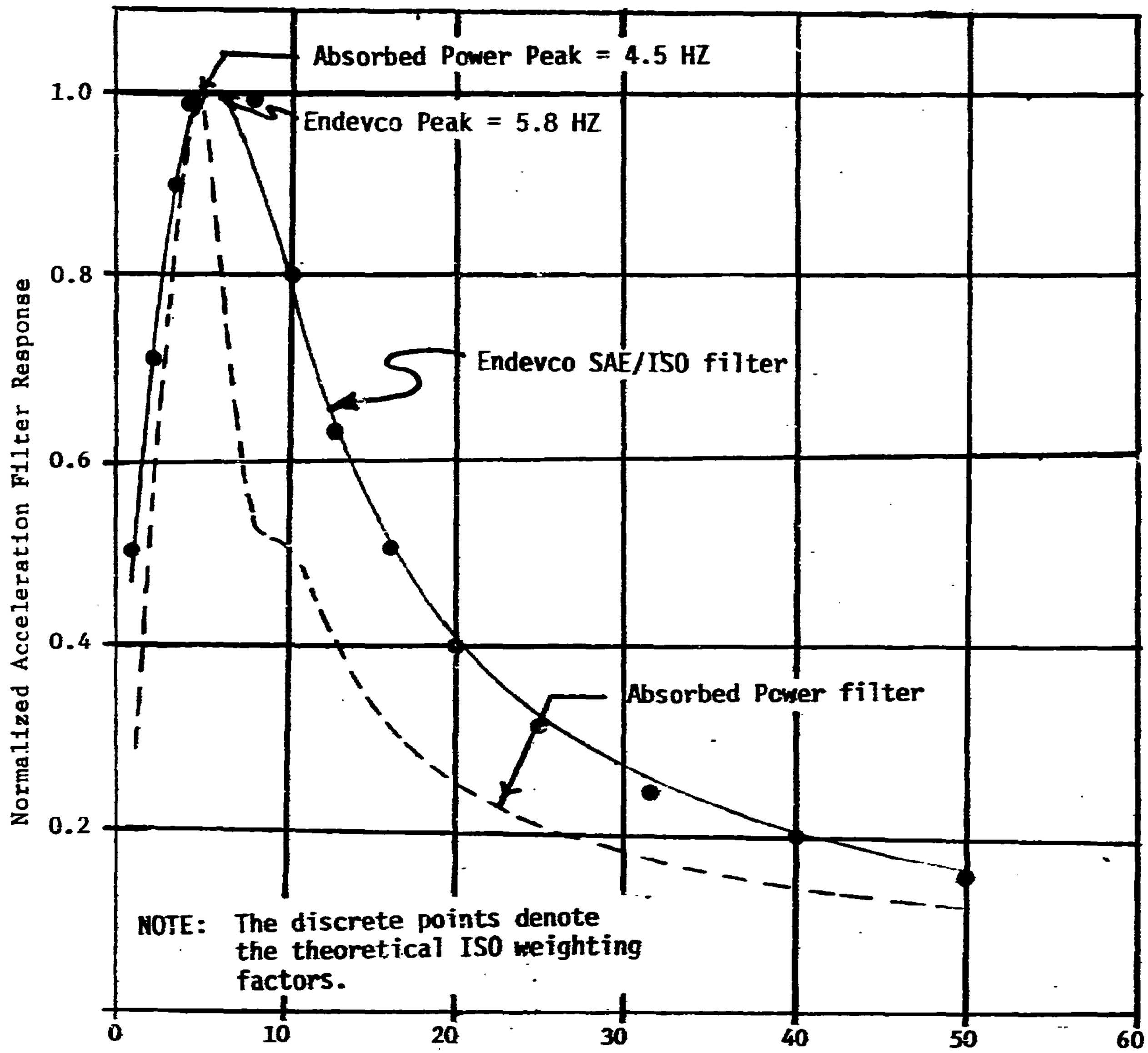


Figure 31. Normalized filter responses

REGRESSION LINE: $Y = 0.206 + 0.995X$

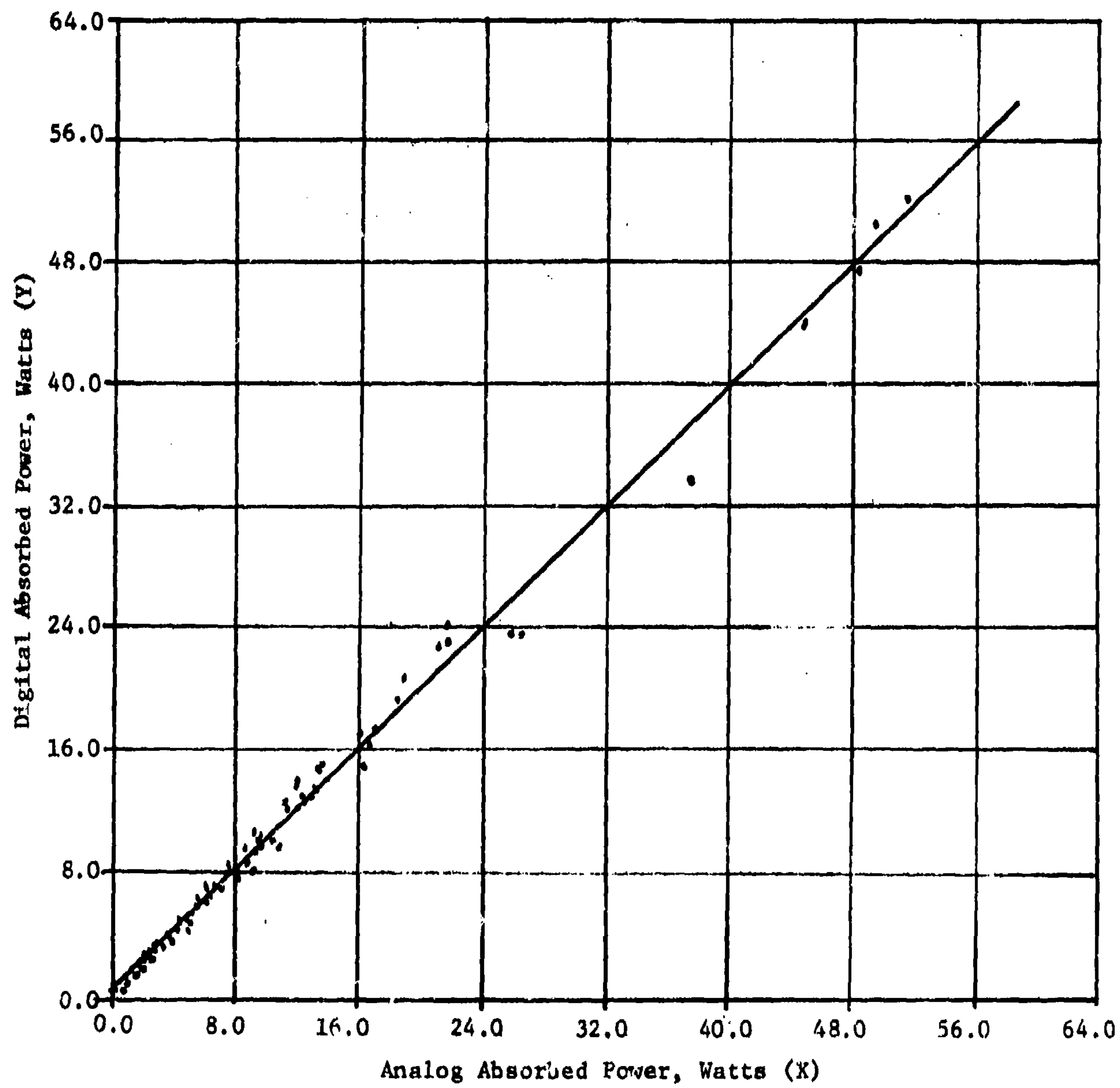


Figure 32. Self-consistency analysis for absorbed power

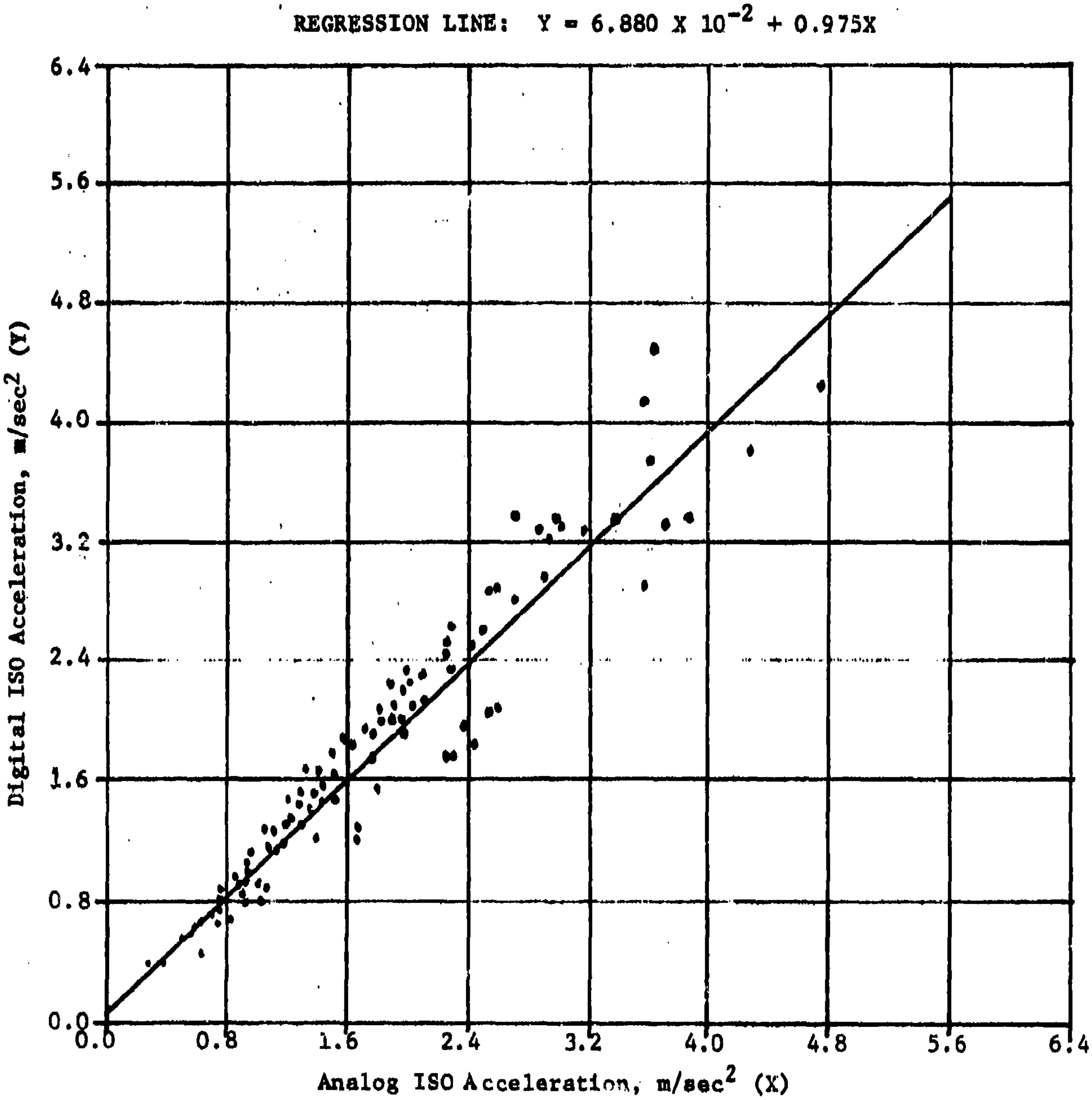


Figure 33. Self-consistency analysis for ISO weighted acceleration

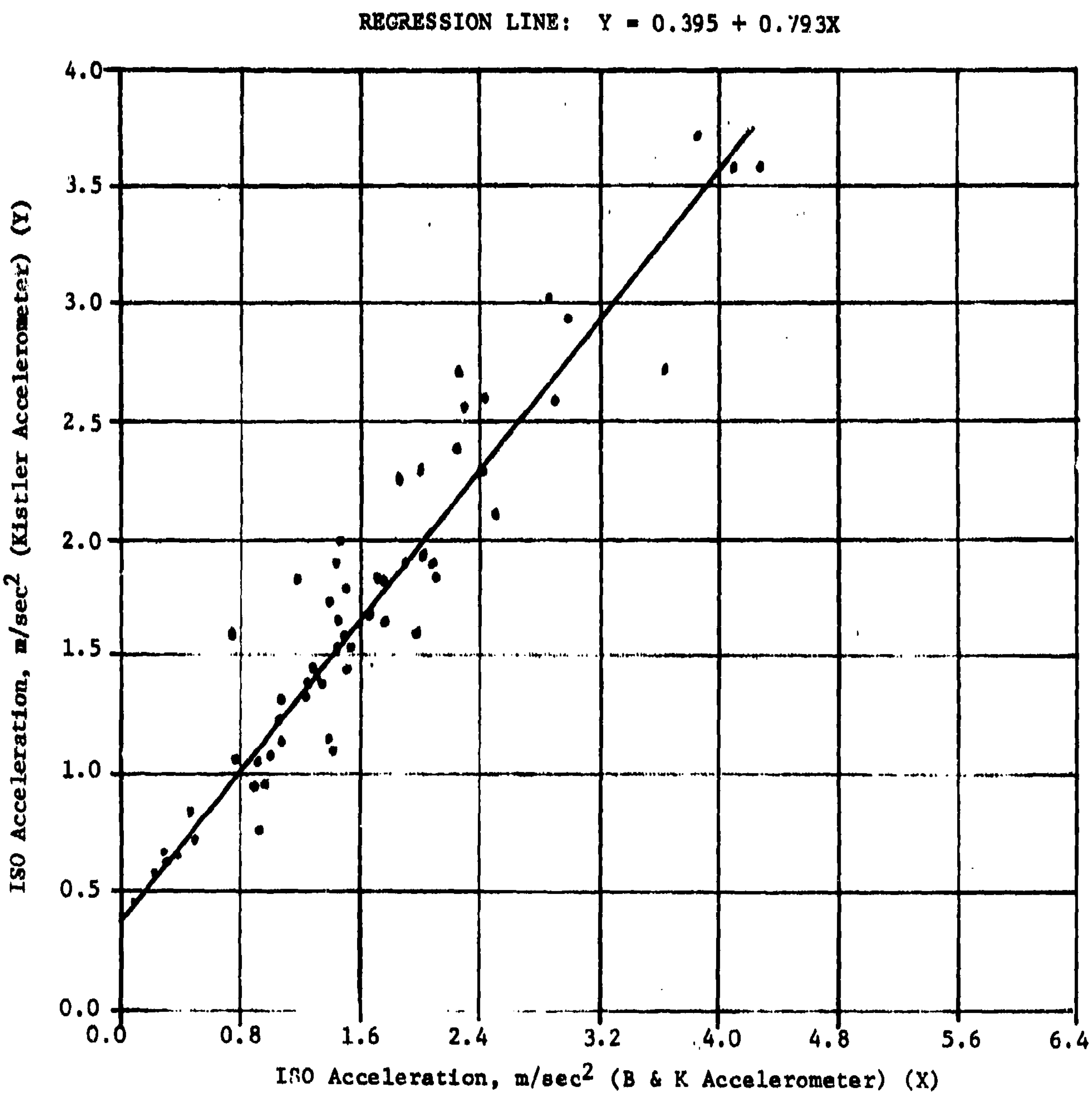


Figure 34. Signal source consistency based on ISO acceleration. Regression of Y (Kister accelerometer) on X (B & K accelerometer)

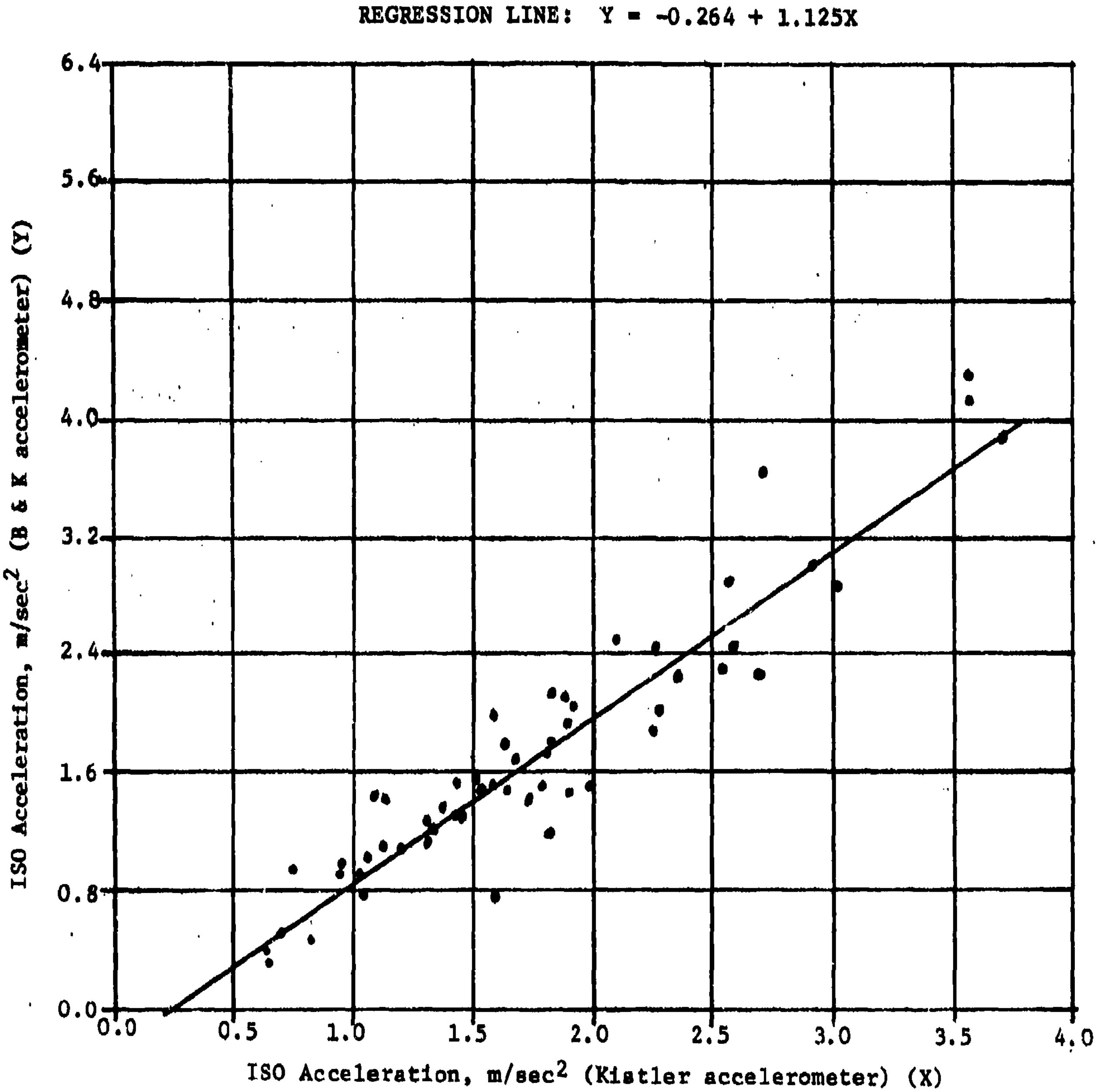


Figure 35. Signal source consistency based on ISO acceleration. Regression of Y (B & K accelerometer) on X (Kistler accelerometer)

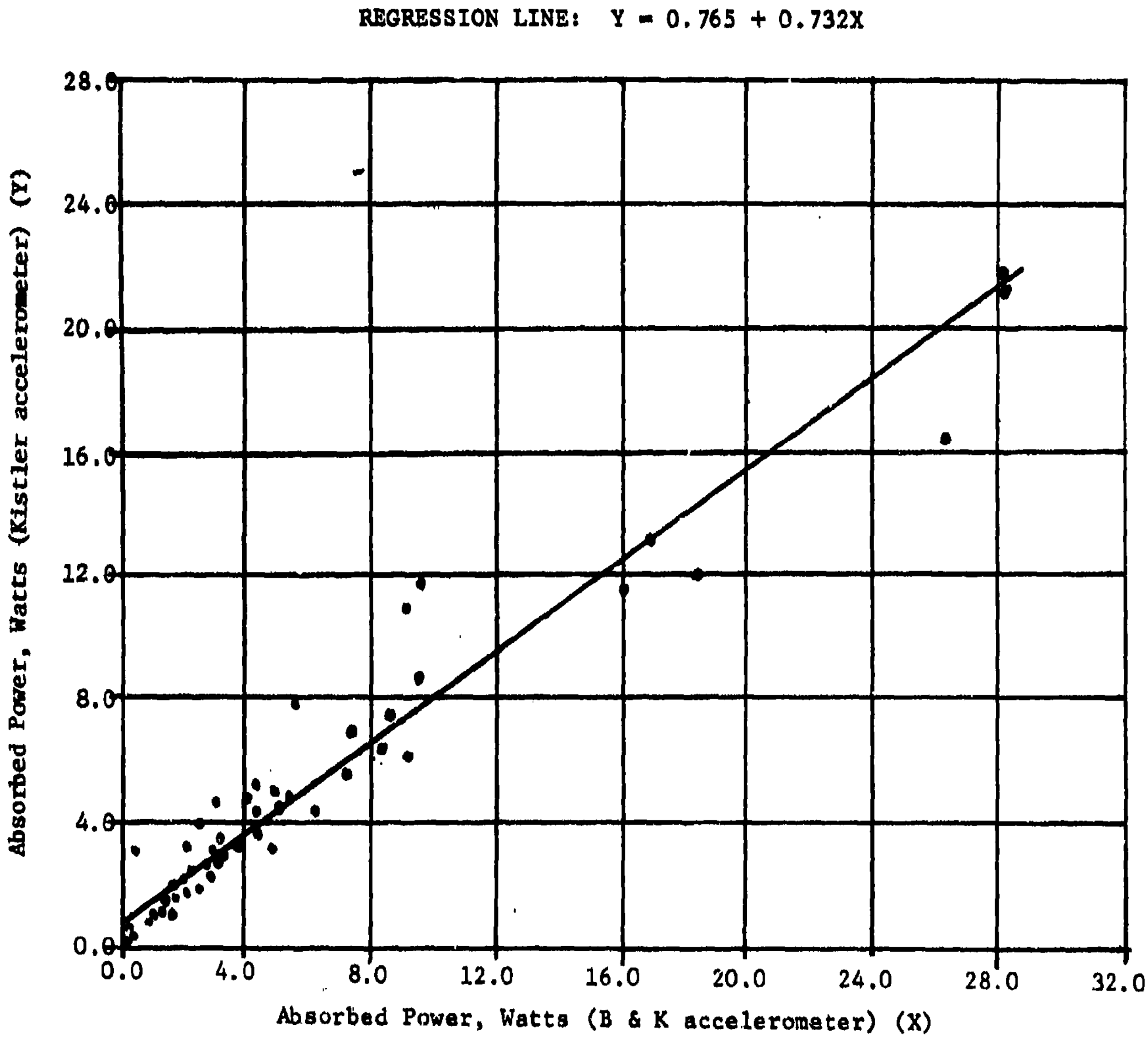


Figure 36. Signal source consistency based on absorbed power. Regression of Y (Kistler accelerometer) on X (B & K accelerometer)

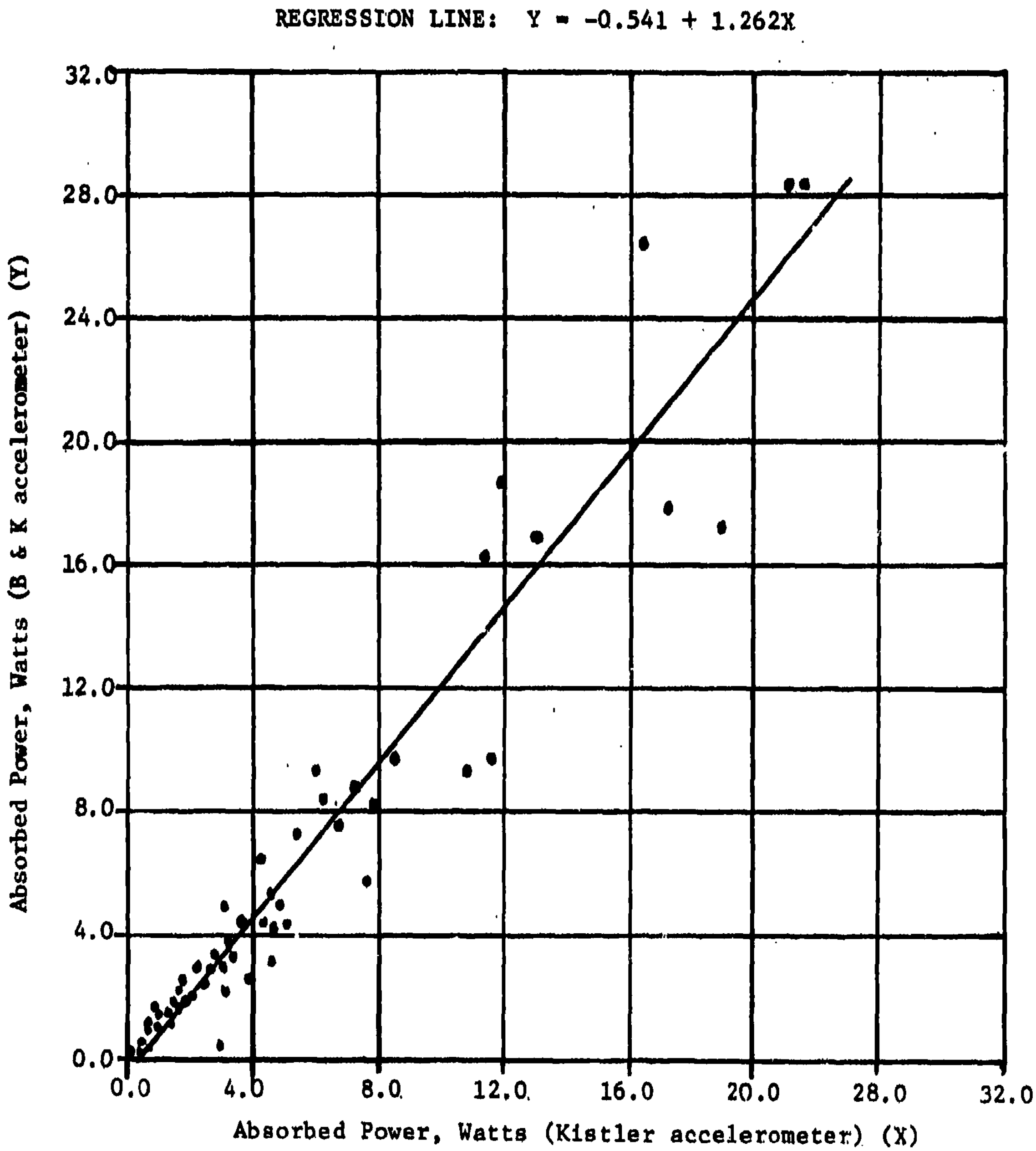


Figure 37. Signal source consistency based on absorbed power. Regression of Y (B & K accelerometer) on X (Kistler accelerometer)

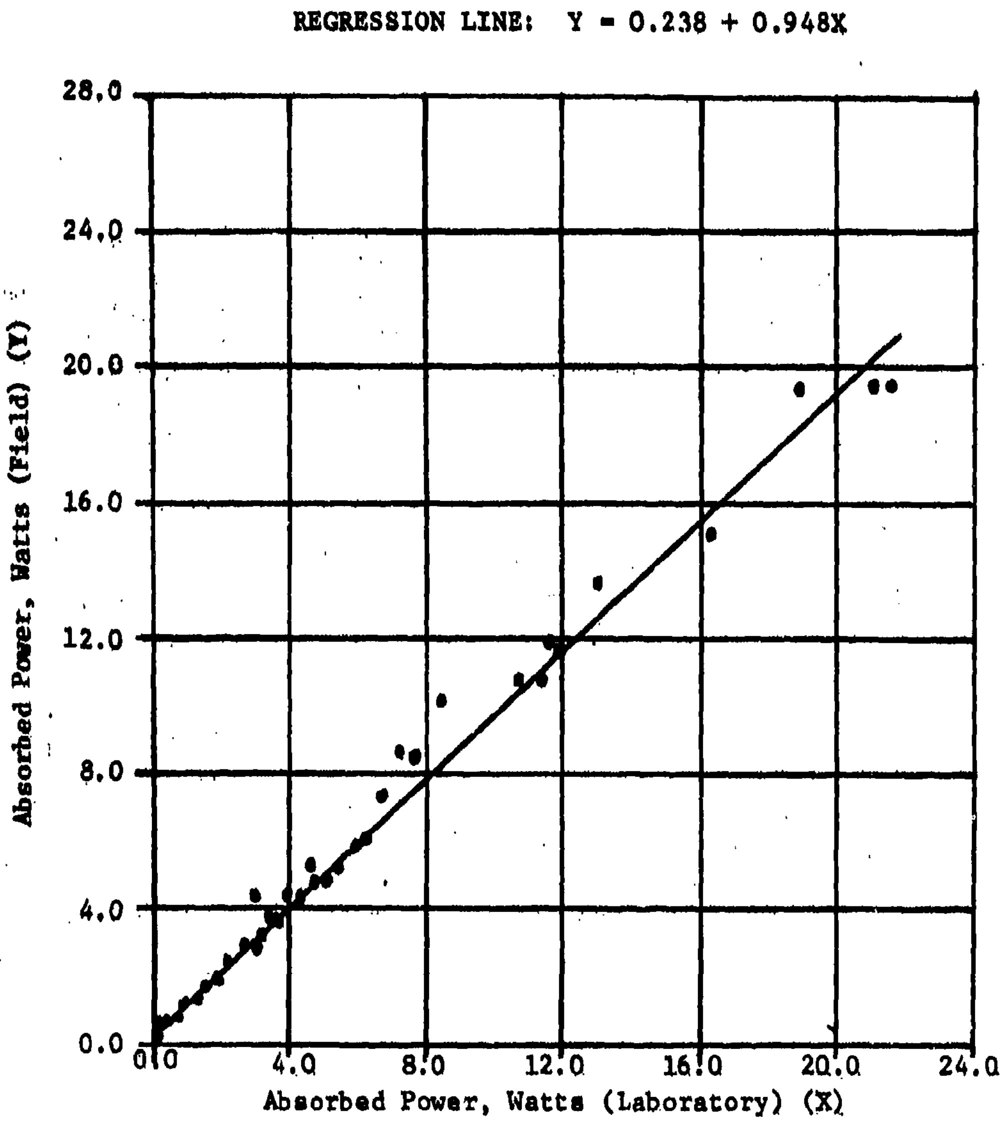


Figure 38. Laboratory and field ride meter consistency based on absorbed power. Regression of Y (field results) on X (laboratory results)

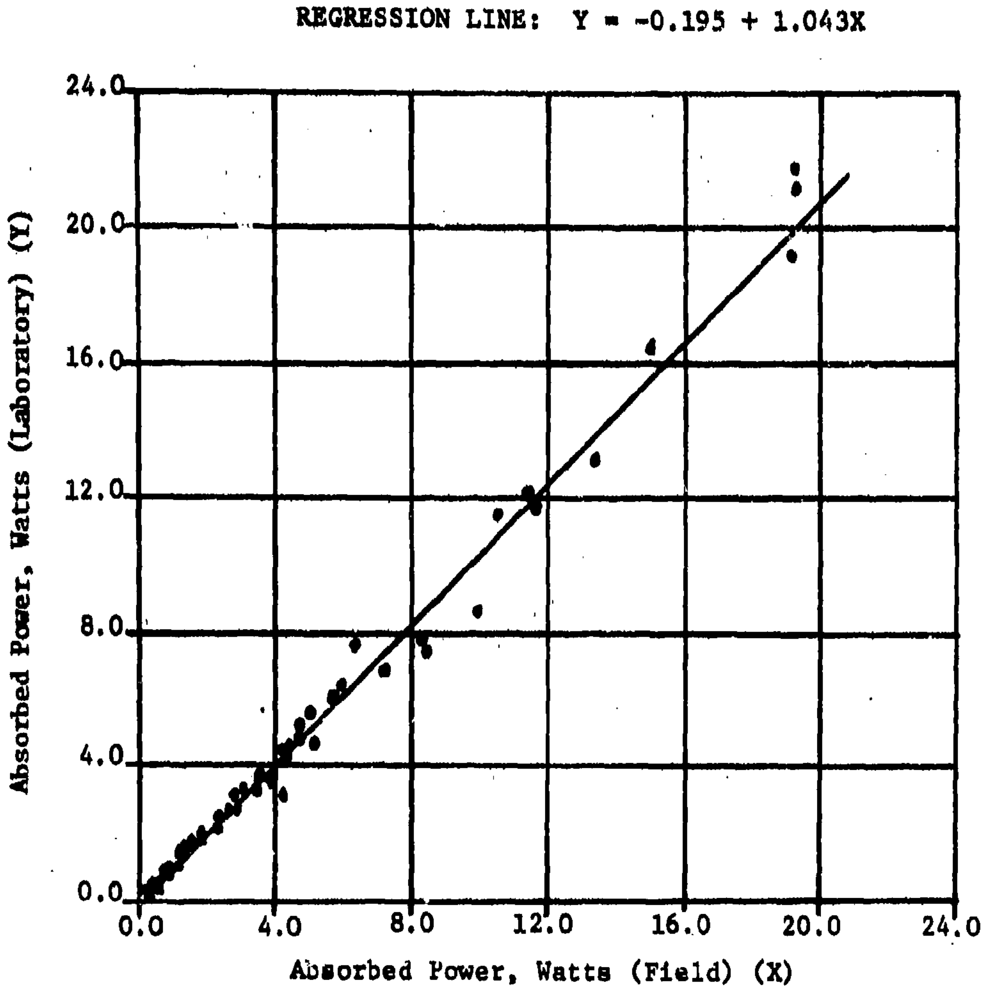


Figure 39. Laboratory and field ride meter consistency based on absorbed power. Regression of Y (laboratory results) on X (field results)

REGRESSION LINE: Y = -7.062 + 0.975X

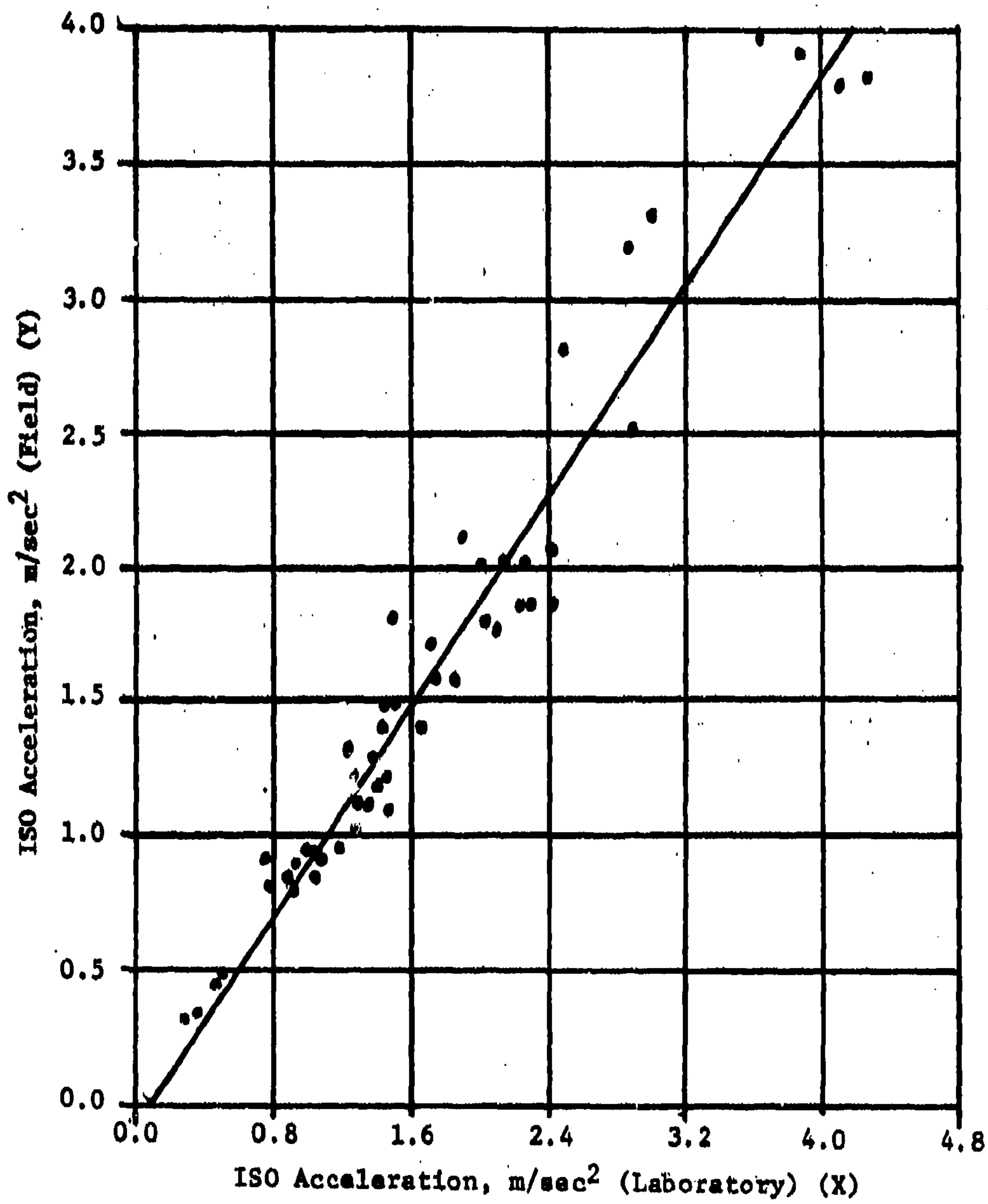


Figure 40. Laboratory and field ride meter consistency based on ISO acceleration. Regression of Y (Field results) on X (laboratory results)

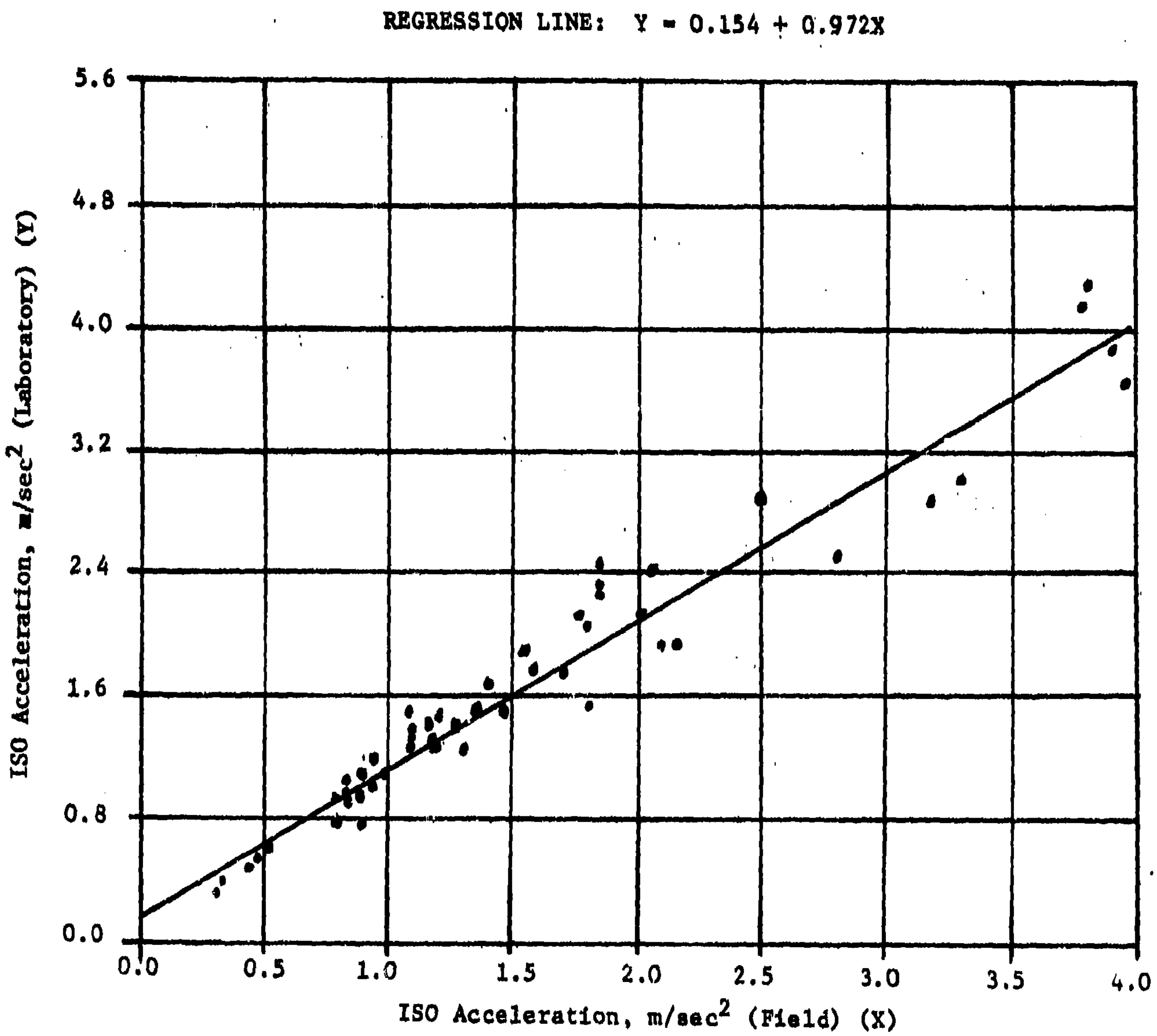


Figure 41. Laboratory and field ride meter consistency based on ISO acceleration. Regression of Y (laboratory results) on X (field results)

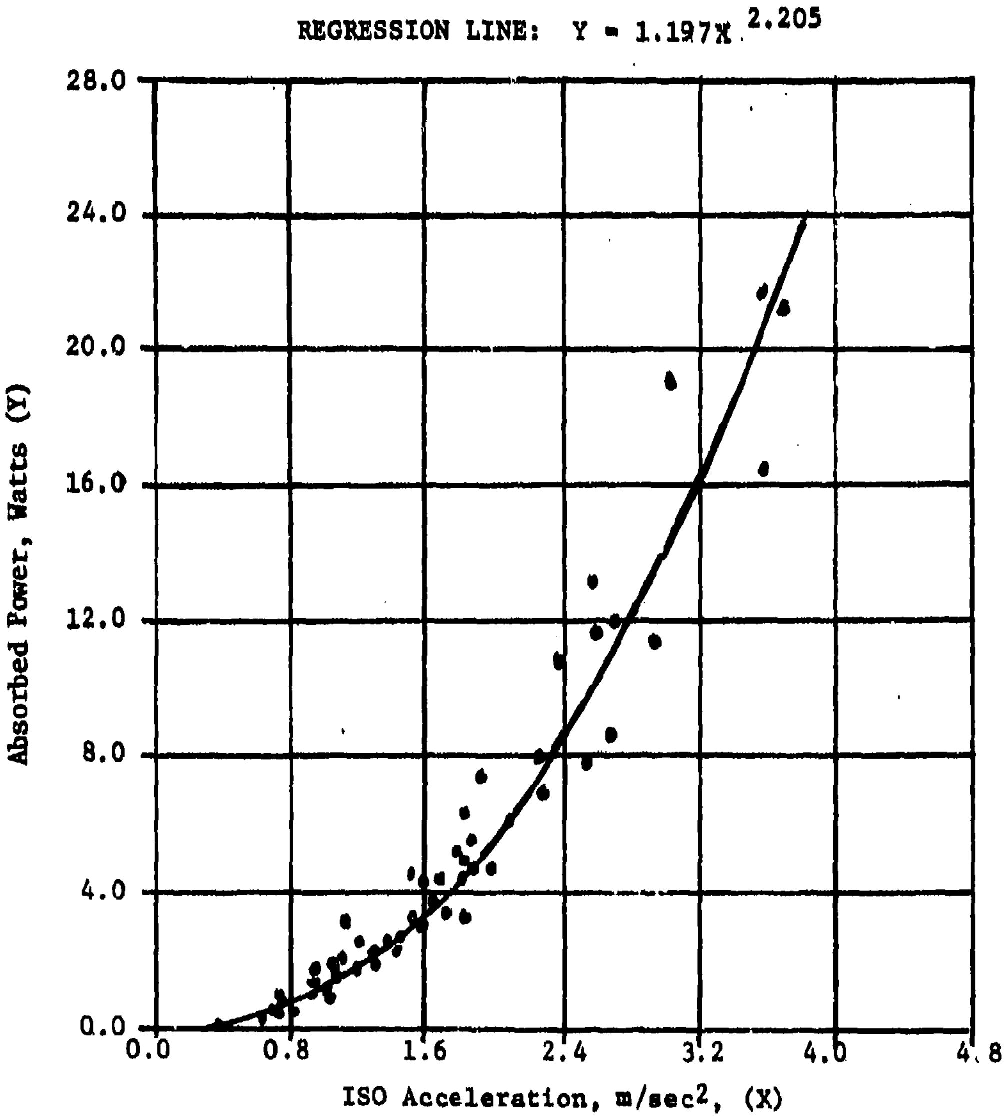


Figure 42. Relation between vibration measures
Regression of Y (absorbed power) on X (ISO acceleration)
both calculated from outputs of Kistler accelerometer

REGRESSION LINE: $1.578X^{2.051}$

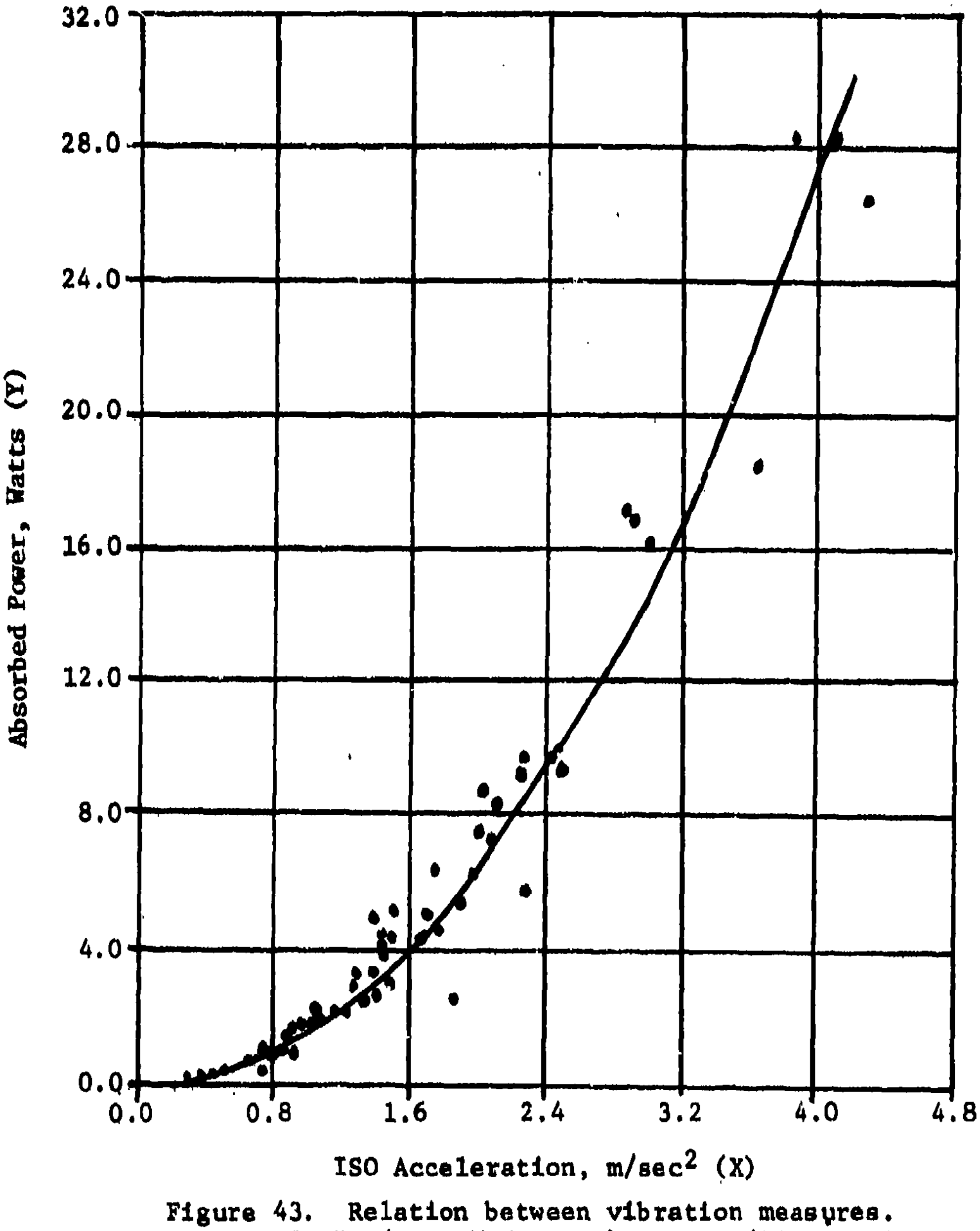


Figure 43. Relation between vibration measures. Regression of Y (absorbed power) on X (ISO acceleration) both calculated from outputs of B & K accelerometer

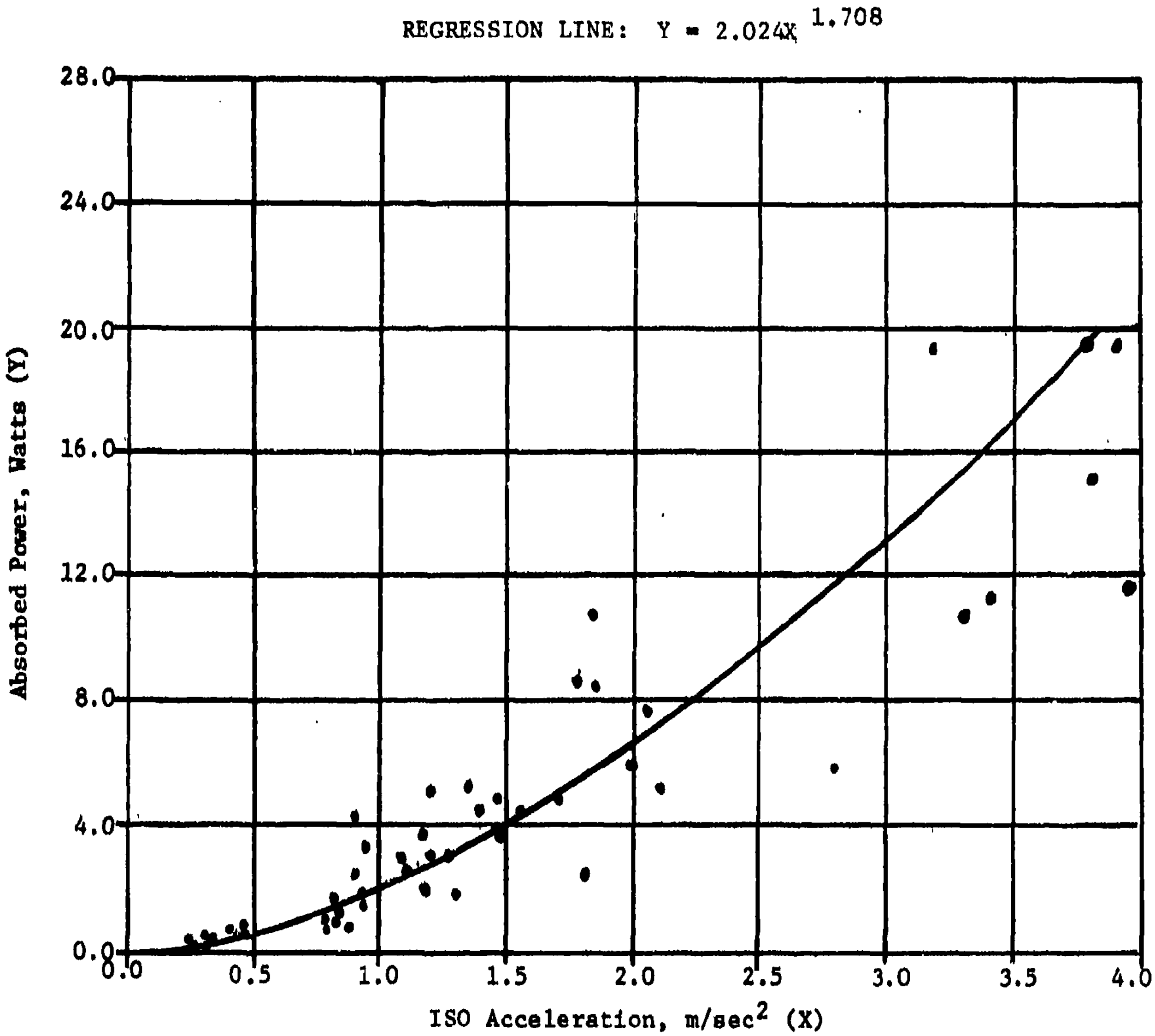


Figure 44. Relation between vibration measures. Regression of Y (absorbed power) on X (ISO acceleration) based on the respective field-recorded outputs of Kistler and B & K accelerometers